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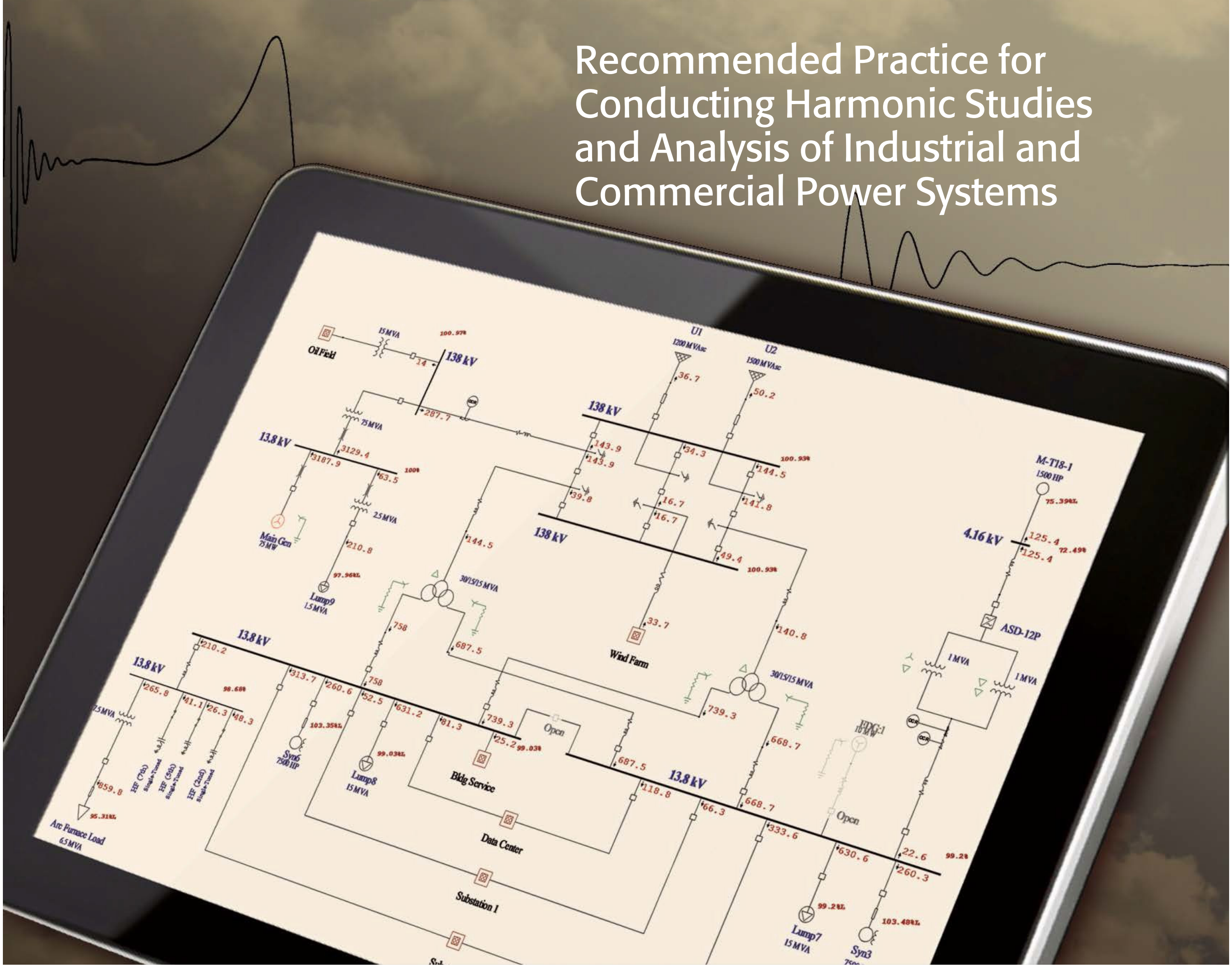
IEEE Std 3002.8™-2018

Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems



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IEEE Std 3002.8™-2018

IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems

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IEEE-SA Standards Board

Abstract: Harmonic studies and analysis of industrial and commercial power systems are described. The basic concepts involved in such studies are described first. This is followed by a discussion of how to determine the need for a harmonic study, how to assemble the required data, how to recognize potential problems, and how to implement corrective measures.

Keywords: commercial power system, harmonics, harmonic analysis, harmonic analysis methods, harmonic analysis tools, harmonic distortion, harmonic filters, harmonic frequency scan, harmonic impedance, harmonic limits, harmonic load flow, harmonic mitigation, harmonic power flow study, harmonic sources, harmonic studies, IEEE 3002.8™, industrial and commercial power systems, industrial power system, interharmonics, resonance, system modeling

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Introduction

This introduction is not part of IEEE Std 3002.8™-2018, IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems.

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When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

— Power Systems Design (3001 series)
— Power Systems Analysis (3002 series)
— Power Systems Grounding (3003 series)
— Protection and Coordination (3004 series)
— Emergency, Standby Power, and Energy Management Systems (3005 series)
— Power Systems Reliability (3006 series)
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In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3002.8™

The material in this recommended practice originally comes from Chapter 10 of the *IEEE Brown Book*™, IEEE Std 399™-1997, Recommended Practice for Industrial and Commercial Power Systems Analysis but includes major modifications based on the latest technological advancements.

This publication provides a recommended practice for conducting harmonic studies and analysis of power systems in commercial and industrial facilities. It is likely to be of greatest value to the power-oriented engineer with limited commercial or industrial plant experience. It can also be an aid to all engineers responsible for the electrical design of commercial and industrial facilities. However, it is not intended as a replacement for the many excellent engineering texts and handbooks commonly in use, nor is it detailed enough to be a design manual. It should be considered a guide and general reference on analysis of commercial and industrial facilities.

Topics of this standard are organized in the following sequence:

a) Harmonic-analysis objectives

b) Harmonic-analysis methodologies and applicable standards
c) System and component models for use in computer simulations for harmonic analysis
d) Data required for computer simulations
e) Common data collection and preparation procedures
f) Importance of model and data validation
g) Typical harmonic-analysis study scenarios, solution parameters, and results and reports interpretation
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IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to conduct harmonic studies and analysis of industrial and commercial power systems. The basic concepts are described first. This is followed by a discussion of how to determine the need for a harmonic-analysis study, how to assemble the required data, how to recognize potential problems, and how to implement corrective measures.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

CIGRE Working Group 36, 05, "Harmonics—characteristic parameters, methods of study, estimates of existing values in the network," Electra, no. 77, pp. 35-54, 1981.[1]

IEC/TR 61000-3-6, Electromagnetic compatibility (EMC)—Part 3-6: Limits—Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.[2]

IEEE Power Engineering Society, "Tutorial on harmonics modeling and simulation," Publication No. 98TP125-0. Piscataway, NJ: Institute of Electrical and Electronics Engineers, 1998.[3,4]

IEEE Power Engineering Society Transmission and Distribution Committee Task Force on Harmonics Modeling and Simulation, "Test systems for harmonic modeling and simulation," IEEE Transactions on Power Delivery, vol. 14, no. 2, pp. 579-587, April 1999, http:// dx .doi .org/ 10 .1109/ 61.754106.

[1]CIGRE publications are available from the Council on Large Electric Systems (http://www.e-cigre.org/).
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IEEE Std 18™, IEEE Standard for Shunt Power Capacitors.

IEEE Std 519-2014™, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.

IEEE Task Force on the Effects of Harmonics on Equipment, "Effects of harmonics on equipment," IEEE Transactions on Power Delivery, vol. 8, no. 2, pp. 672-680, April 1993, http://dx.doi.org/10.1109/61.216874.

Prabhakara, F. S., R. L. Smith, and R. P. Stratford, Industrial and Commercial Power Systems Handbook. New York: The McGraw-Hill Companies, 1996.

Shipp, D. D., "Harmonic analysis and suppression for electrical systems supplying static power converters and other nonlinear loads," IEEE Transactions on Industry Applications, vol. 1-A-15, no. 5, pp. 453-458, Sept./Oct. 1979.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[5]

The following definitions are adapted from IEEE Std 519™.

harmonic (component): A component of order greater than one of the Fourier series of a periodic quantity. For example, in a 60 Hz system, the harmonic order 3, also known as the *third harmonic*, is 180 Hz.

interharmonic (component): A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., 50 Hz or 60 Hz).

***I-T* product**: The inductive influence expressed in terms of the product of root-mean-square current magnitude (I), in amperes, times its Telephone Influence Factor (TIF).

kV-T product: Inductive influence expressed in terms of the product of root-mean-square voltage magnitude (V), in kilovolts, times its Telephone Influence Factor (TIF).

maximum demand load current: This current value is established at the Point of Common Coupling and should be taken as the sum of the currents corresponding to the maximum demand during each of the 12 previous months divided by 12.

notch: A switching (or other) disturbance in the normal power voltage waveform, lasting less than 0.5 cycles, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles.

notch depth: The average depth of the line voltage notch from the sine wave of voltage.

notch area: The area of the line voltage notch. It is the product of the notch depth, in volts, times the width of the notch measured in microseconds.

Point of Common Coupling (PCC): Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.

[5] *IEEE Standards Dictionary Online* subscription is available at: http://dictionary.ieee.org.

pulse number: The total number of successive non-simultaneous commutations occurring within the converter circuit during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage; that is, the number of pulses present in the dc output voltage in one cycle of the supply voltage.

short-circuit ratio: At a particular location, the ratio of the available short-circuit current, in amperes, to the load current, in amperes.

Telephone Influence Factor (TIF): For a voltage or current wave in an electric supply circuit, the ratio of the square root of the sum of the squares of the weighted root-mean-square values of all the sine-wave components (including alternating current waves both fundamental and harmonic) to the root-mean-square value (unweighted) of the entire wave.

Total Demand Distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, to the maximum demand current expressed as a percent value. Harmonic components of order greater than 50 may be included when necessary.

Total Harmonic Distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, to the fundamental component expressed as a percent value. Harmonic components of order greater than 50 may be included when necessary.

4. Introduction

This recommended practice discusses the basic concepts involved in studies of harmonic analysis of industrial and commercial power systems. The need for such an analysis, recognition of potential problems, corrective measures, required data for analysis, and benefits of using a computer as a tool in a harmonic-analysis study are also addressed in this recommended practice.

Any devices with nonlinear voltage-current characteristics generate harmonics. The main sources of harmonics in industrial and commercial power systems are static power converters used as rectifiers for various industrial processes and for other applications such as adjustable/variable speed drives, uninterruptible power system (UPS), chargers, switched-mode supplies, static frequency converter, cycloconverters, etc. Arc furnaces and saturated magnetic devices are also harmonic sources. Since nonlinear devices represent an ever-increasing percentage of the total load in industrial and commercial electrical power distribution systems, harmonic studies become an important part of overall system design and operation. Fortunately, the available software for harmonic analysis has also grown. Guidelines for the acceptance of harmonic distortion at Point of Common Coupling (PCC) level are defined in IEEE Std 519™, and the interharmonic effects to voltage flickers at other system levels are also discussed. By modeling power system impedances as a function of frequency and harmonic sources as injecting currents or forced voltages, a harmonic study can be made to determine the effect of the harmonic contributions from nonlinear loads on the voltages and currents in the power system.

Most commercial software packages calculate and provide the following results while performing harmonic analysis.

a) Harmonic bus voltages and branch current flows in the network

b) Impedance versus frequency spectrums for determining resonance conditions

c) Performance indices that quantify the effect of harmonics on voltage and current waveforms, electro-magnetic interference, with telephone lines, etc.

d) Individual and total harmonic bus voltage and branch current distortion limit violation alerts

e) Alerts indicating equipment (cable, transformer, capacitor bank, harmonic filter, etc.) overloading or overstress

The software can also help in sizing and locating capacitors or passive filters for minimizing the effect of harmonics and optimizing system performance.

In cases where a system cannot be easily or accurately modeled in the frequency domain, time-domain simulation programs such as the Electro Magnetics Transients Program (EMTP) are used for harmonic analysis. The output waveforms of these simulations are then post-processed using the Fast Fourier Transform (FFT) to yield the calculated harmonic spectrum.

System modeling details described here particularly apply to industrial and commercial systems at low and medium voltages, but the basics are also applicable to other systems and higher voltages. This standard does not deal with active filters as part of the filter design; however, some reference is made to their applications.

It may be said at the outset that harmonic filter design is very closely linked to power factor (PF) requirements of the system (often based on minimizing utility tariffs) and both must be considered at the same time. PF compensation capacitors are also used for a variety of other purposes, such as transformer and conductor sizing, motor starting, and voltage support. PF compensation studies will always take into account the shift in system resonance points and the absorption of harmonics associated with introduction of power factor capacitors.

The current revision of IEEE Std 519 should be referred to for general information and particularly for harmonic generation from static power converters and other harmonic sources. An exhaustive reference list is provided in Annex A, which should be referred to for details in specific areas.

5. Background

In the context of power system harmonic concerns, a nonlinear load or device is one that does not draw a sinusoidal current when excited by a sinusoidal voltage. The most common nonlinear devices are switching devices, such as solid-state converters, which force the conduction of currents for only certain periods and, to a lesser extent, saturatable impedance devices such as transformers with nonlinear voltage versus impedance characteristics. In computer modeling and simulation, a nonlinear load or device is considered a source of harmonic currents, where harmonic frequencies are generally integer multiples of the system frequency. However, certain nonlinear loads, such as an arc furnace or a cycloconverter, may also have non-integer harmonic frequencies in addition to the expected integer harmonics.

Harmonics, by definition, occur in every cycle of the fundamental component and are calculated as part of the steady-state solution. However, exceptions exist, and harmonics may vary from cycle to cycle. These are termed *time-varying harmonics*. Also, harmonics may appear in quasi-steady-state or transient situations, such as in magnetization inrush current of a transformer. This standard does not deal with transient harmonics or time-varying harmonics, which require harmonic source models as a function of time and involve time domain simulations.

The generated harmonic frequencies are dependent upon the type of nonlinear load or device. Most nonlinear loads or devices produce odd harmonics with small even harmonics. However, loads such as arc furnaces produce the entire spectrum of harmonics: odd, even, and non-integer harmonics in between (non-integer harmonics are also referred to as *interharmonics*). Generally, the amplitude of the harmonics decreases as the frequency (or the harmonic order) increases.

An ideal current source is one that provides a constant current irrespective of the system impedance seen by the source. In most studies for industrial applications, the nonlinear load or the harmonic source is considered an ideal current source without a Norton's impedance across the source (i.e., Norton impedance is assumed

to be infinite). This approximation is generally reasonable and yields satisfactory results. When the nonlinear device acts like a voltage source, meaning that it has relative fixed voltage waveform distortion rather than fixed current waveform distortion (e.g., a pulse-width-modulated [PWM] inverter, or an arc furnace, or a utility connection), a Thevenin equivalent voltage source model can be used.

During harmonic analysis the system is subjected to harmonic current injections and/or harmonic voltage affection at multiple frequencies, the network is solved for voltage and current at each frequency separately. The total voltage or current in an element is then found either by a root-mean-square sum or arithmetic sum, using the principle of superposition. The effect of harmonic current propagation through the network, including the power source, produces distortion of the voltage waveform depending upon harmonic voltage drops in various series elements of the network. Therefore, the voltage distortion at a given bus is dependent on the equivalent source impedance; the smaller the impedance, the better the voltage quality. Note that the harmonic sources, which are nonlinear loads, are not the sources of power, but are the cause of additional active and reactive power losses in the system.

6. Analysis objectives

With the growing proliferation of nonlinear loads in commercial buildings and industrial plants, which may be in the range of 30% to 50% of the total load, the effects of harmonics within the system and their impact on the utility and neighboring loads need to be examined before any complaints are made for equipment damage or production loss.

The following situations may necessitate a harmonic study, which should include recommendations for mitigating the effects of harmonics:

— Compliance with IEEE Std 519, which defines the current distortion limits a user should meet at the Point of Common Coupling (PCC) with the utility. Voltage distortion limits are also defined as a basis for the system design. The voltage distortion limits are primarily intended for the utility to provide a good sine wave voltage; however, an individual user is expected to use the voltage limits as a basis for the system design. The chances are that if the current distortion limits are met, the voltage distortion limits will also be met, except in some unusual circumstances.

— A history of harmonic-related problems, such as failure of power-factor compensation capacitors, overheating of cables, transformers, motors, etc., or misoperation of protective relays or control devices.

— Plant expansion where significant nonlinear loads are added or where a significant amount of capacitance is added.

— Design of a new facility or power system where the load flow, power factor compensation, and harmonic analyses are considered as one integrated study to determine how to meet the reactive power demands and harmonic performance limits.

When harmonics appear to be the cause of system problems, it is necessary to determine the resonant frequencies at the problem sites. With PF correction capacitor banks, a parallel system resonance can occur at or near one of the lower harmonic orders (3, 5...). This resonance can be critical if excited by a harmonic current injection at that frequency. Refer to 7.4 for an approximate calculation of harmonic resonant frequency. An estimate of the resonant frequencies is very useful for an initial evaluation.

Reasons to conduct harmonic-analysis studies of industrial and commercial power systems include, but may not be limited to:

1) Benchmark existing system and collect data to calibrate model by measurements of existing system with well-defined test plan.

2) Identify location, type, and magnitude of harmonic sources in the system.
3) Simulate impacts of these harmonic sources on system voltages and currents.
4) Study harmonic penetrations to the system.
5) Calculate voltage and current harmonic distortions on each individual frequency and Total Harmonic Distortion (THD).
6) Check if there exist any violations in harmonic voltage and current distortion level.
7) Calculate other harmonic indices and compare them to the standard or code limitations.
8) Identify if the system has parallel or series resonance conditions.
9) Design harmonic filters and test harmonic filters.
10) Test transformer phase shift and analyze its effects on harmonic current cancellation and harmonic distortion deduction.
11) Test other harmonic mitigation designs and performance.

More specifically, during the system design phase, it is important that the following factors be considered in the study:

a) Model harmonic sources from nonlinear loads and power electronics devices, simulate their impacts to the system, and assess harmonic voltage and current distortion levels.
b) Calculate all harmonic indices, both voltage and current.
c) Compare the distortion levels and harmonic indices with the standard and code limits to see if there are any violations.
d) Identify system parallel or series resonance frequencies.
e) Check if there are any harmonic source frequencies at or near the system parallel resonance points.
f) If there are harmonic source frequencies at or near the system parallel resonance points, assess the overvoltage conditions at these frequency points.
g) If there are harmonic source frequencies at or near the system series resonance points, assess the over-current conditions at involved capacitor banks.
h) If necessary, design and test harmonic mitigation methods such as:
    1) Install harmonic filters to reduce the harmonic distortion levels and shift resonance frequencies to less harmful regions.
    2) Use transformer phase shift to cancel harmonics and obtain overall harmonic distortion reduction.
i) Simulate the final system for overall harmonic voltage and current distortions after harmonic mitigations are implemented.

In the system operation phase, harmonic-analysis studies should be done to simulate various operating conditions and configurations to verify if there are any excessive harmonic distortions and harmful parallel resonances under all possible operating conditions.

In the system expansion phase, harmonic-analysis studies should be performed to model and simulate system changes and prevent harmonic distortion deterioration and new parallel resonance and overvoltage situations which could be introduced by new harmonic sources added to the system and system impedance changes due to new configurations.

7. Methodology and standards

7.1 General harmonic-analysis methodology

In harmonic-analysis computer simulation, distorted voltages and currents due to nonlinear devices are modeled as harmonics sources, and network power flow solutions are found with these harmonic sources. The general approach is to simulate harmonic current sources by injecting the harmonic currents into the network and simulate harmonic voltage sources by placing harmonic voltage at buses, and calculate voltages and currents in the network as a function of harmonic sources at each individual harmonic frequency. When network voltages and currents are solved, different harmonic indices are then computed at critical locations and compared to standard or code limits, or any applicable contractual limitations. If violations are found, harmonic mitigations will be required to reduce harmonic distortions. Harmonic mitigation methods usually include one or a combination of design and installation of harmonic filters, both in static types or active types, configuration and utilization of parallel transformer with phase-shifts, and harmonic load rebalancing. If the system has capacitor banks or other significant capacitive loads or devices, a frequency scan that computes driving point (or Thevenin equivalent) impedance at designated buses should be performed to identify parallel resonance locations and resonance frequencies. Once the parallel resonances are identified, overvoltage conditions at the resonant locations and resonant frequencies should be computed and assessed. For excessive voltage situations, elimination of resonances or relocation of resonant frequencies should be done through design and placement of harmonic filters to avoid actual parallel resonance and overvoltage situations in the system.

7.2 Harmonic sources

All harmonic sources are referred to as *nonlinear loads* because they draw non-sinusoidal currents when a sinusoidal voltage is applied. The non-sinusoidal current may be due to the inherent characteristic of the load (e.g., arc furnaces), or due to a switching circuit (e.g., a 6-pulse converter that forces conduction of currents for only certain periods). In industrial and commercial power systems there may be many such harmonic sources distributed throughout the system.

The harmonic study requires knowledge of the harmonic currents or voltages generated by nonlinear loads or nonlinear sources. There are several options to acquire data for harmonic analysis:

a) Obtain the harmonic spectrum of the source from the equipment manufacturer. This is particularly important in cases where new technology or non-standard equipment is applied.

b) Calculate the generated harmonics by analytical methods where possible, such as at converters or static var compensators.

c) Use computer simulation software that simulates the operation of the power electronics circuit to generate harmonic spectra and waveforms.

d) Apply typical values based on similar applications or published data.

In practice, combinations of all four methods are used to provide reasonable results. However, it should be noted that on-site harmonic measurements may not yield the worst-case harmonic spectrum, depending on the equipment operating modes at the time the measurements are made. Calculation of harmonics by analytical methods can be challenging, as it requires determining an equation for the subject waveform and performing a Fourier analysis on that equation.

Since the system configuration and load continually change, the harmonics also change and it would be a formidable task to study all such conditions. Usually, the worst operating condition is determined, and the design is based on the “worst-generated” harmonics ratio. However, it needs to be recognized that even with the “worst-generated” harmonic case, the harmonic flows within different elements of the network can be

different, depending on the number of transformers or tie breakers in service. This necessitates that for the "worst-generated" case, the "worst-operating" cases(s) must be analyzed.

One other difficulty in the analysis arises from the fact that when multiple harmonic sources are connected to the same bus (or different buses), the phase angles between the harmonics of the same order are usually not known. Generally speaking, arithmetic addition of harmonic magnitudes is reasonable if the harmonic sources are similar and have similar operating load points. However, this approach can lead to a more conservative filter design and distortion calculations if the sources are different or operate at different load points. Determination of phase angles of harmonics and vectorial addition can be quite a complex and expensive approach for general industrial application. This is often resolved by simplifying assumptions based on experience or by field measurements. More advanced techniques are used in high-voltage dc transmission and other utility applications where precision is important.

Industrial harmonic studies are usually represented on a single-phase basis, i.e., based on the assumption that the system is balanced and positive sequence analysis applies. A three-phase study is warranted only if the system or the load is severely unbalanced, or a four-wire system with single-phase loads exists. However, with the development and operation of electrical railway systems in some countries, more and more unbalanced three-phase systems have been observed. In such a situation it will be desirable to determine the harmonics generated in all three phases. The cost of a three-phase study could be higher than a single-phase study and should be used only when such an expense and purpose can be justified.

7.3 Effects of harmonics

The effects of harmonics are described here only in the context of the analytical harmonic system study, details of these effects can be found in referenced literature. IEEE Std 519 and Prabhakara, Smith, and Stratford's *Industrial and Commercial Power Systems Handbook* deal with the subject in detail. The effects of harmonics in a power system are pervasive in that they influence system losses, system operation, and system performance. Unless the harmonics are controlled to acceptable limits, the power equipment and, even more so, the electronic equipment may be damaged, resulting in costly system outages.

The effects of harmonics are due to both current and voltage, although current-produced effects are more likely to be seen in day-to-day performance. Voltage effects are more likely to degrade the insulation and hence shorten the life of the equipment. The following describes some of the common effects of harmonics:

a) Increased losses within the equipment and associated cables, lines, etc.
b) Pulsating and reduced torque in rotating equipment
c) Premature aging due to increased stress in the equipment insulation
d) Increased audible noise from rotating and static equipment
e) Misoperation of equipment sensitive to waveforms
f) Substantial amplification of currents and voltages due to resonances
g) Communication interference due to inductive coupling between power and communication circuits

Generally, harmonic studies involving harmonic flows and filter design do not involve detailed analysis of the effects of harmonics if the limits imposed by the user or by a standard are met. However, in specific cases, analysis of harmonics penetrating into rotating equipment, causing relay misoperation, or interfering with communication circuits may require a separate study.

For additional information, see the report by the IEEE Task Force on the Effects of Harmonics on Equipment.

7.4 Resonance

7.4.1 Introduction

Most power system circuit elements are primarily inductive, therefore the presence of shunt capacitors used for power-factor correction or harmonic filtering can cause cyclic energy transfer between the inductive and capacitive elements at the natural frequency of resonance. At this frequency, the inductive and capacitive reactances are equal.

The combination of inductive (L) and capacitive (C) elements as viewed from a bus of interest, generally the bus at which harmonic currents are injected by a nonlinear load (source bus), can result in either a series resonance (L and C in series) or a parallel resonance (L and C in parallel). As shown in the following sections, the series resonance results in low impedance and parallel resonance in high impedance. At either series or parallel resonance, the net impedance is resistive. In harmonic studies, it is essential that the driving-point impedance, as seen from the harmonic source bus (or other bus of interest), be examined to identify the series and parallel resonance frequencies and resulting impedances.

In practical electrical systems, power factor (PF) correction capacitors are primarily utilized to offset the power factor penalty imposed by the utility. This can create an abnormal situation, because the combination of capacitors and inductive elements in the system can result in either series or parallel resonance or a combination of both, depending upon the system configuration. Usually parallel resonance occurs more often because capacitor banks act in parallel with system impedance (inductive); this can be a matter of concern if the resonant frequency happens to be close to one of the frequencies generated by the harmonic sources in the system.

The result of a series resonance may be the flow of unexpected amounts of harmonic currents through certain elements. A common manifestation of excessive harmonic current flow is inadvertent relay operation, blown fuses, and overheating of cables, etc.

The result of a parallel resonance may be the presence of excessive harmonic voltages across network elements. A common manifestation of excessive harmonic voltages is capacitor or insulation failure.

7.4.2 Series resonance

An example of series resonant circuit is shown in Figure 1. Each circuit element is described in terms of its impedance. The equivalent impedance of the circuit and the current flow are expressed by Equation (1) and Equation (2). This circuit is said to be in resonance when the inductive reactance X_L is equal to the capacitive reactance X_C. The resonant frequency at which $X_L = X_C$ is given by Equation (5).

$$\overline{Z} = R + j(X_L - X_C) \tag{1}$$

$$\overline{I} = \frac{\overline{V}}{R + j(X_L - X_C)} \tag{2}$$

$$= \frac{\overline{V}}{R} \text{ at resonance } \quad (X_L = X_C) \tag{3}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{4}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

Given the relatively low values of series resistance usually found in power equipment, the magnitude of the current in Equation (3) can be large at resonance.

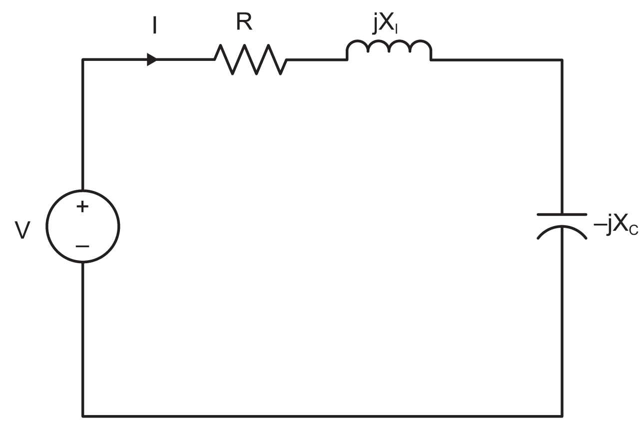


Figure 1—Example circuit for series resonance

Figure 2 shows the equivalent impedance of the circuit in Figure 1 as a function of frequency. The element values are $R = 2\ \Omega$, $L = 3.98$ mH, and $C = 36.09\ \mu$F. It is clear from Equation (1) that the impedance appears capacitive at low frequencies and becomes inductive as the frequency increases, and that resonance occurs at 420 Hz (7th harmonic for a 60 Hz system).

A general measure of the shape of the impedance plot of Figure 2 is often given in terms of the quality factor Q. For a series resonant circuit, the Q is defined in Equation (6) at any angular frequency ω.

$$Q = \frac{\omega L}{R} \tag{6}$$

At the resonant frequency, the Q is generally approximated to the ratio of $\omega_0 L/R_L$ since $R \approx R_L$ as capacitors have negligible resistance. As will be demonstrated later, the parameter Q often plays an important role in filter design because most single-tuned harmonic filters are simple RLC series-resonant circuits. In general, a higher Q produces a more pronounced "dip" in the plot of Figure 2. A lower Q results in a more rounded shape. In most filter applications, the natural quality factor (with no intentional resistance) is relatively high (> 100 at resonant frequency). In special applications it may be necessary to intentionally reduce the Q.

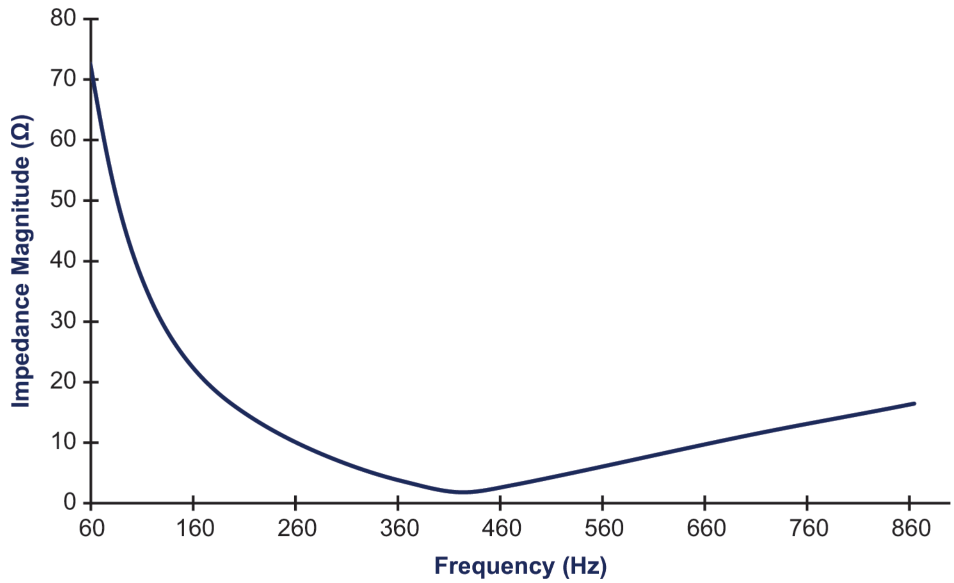


Figure 2—Impedance magnitude versus frequency for series resonant circuit

Typical situations where series resonance can be a problem are shown in the one-line diagrams of Figure 3. In Figure 3 (a), the utility supply is assumed to contain voltage harmonics. The series resonant path is created from the equivalent series impedance from the utility supply and the bus transformer and the PF correction capacitor. In Figure 3 (b), the harmonics are generated inside the plant. The series resonant path involves the two transformer impedances and the PF correction capacitor.

This transformer-capacitor combination could inadvertently act as a filter, and permit the flow of harmonic current at or near the resonant frequency into the capacitor bank. If unplanned, these currents can lead to blown fuses, inadvertent relay operation, and loss-of-life for the capacitor and the transformer.

7.4.3 Parallel resonance

There are many forms of parallel resonant circuits. In general, an inductor must be in parallel with a capacitor to produce parallel resonance. A typical parallel-resonant circuit encountered in power systems is shown in Figure 3. Each element is described by its impedance. This circuit is said to be in parallel resonance when $X_L = X_C$, as in the case of series resonance.

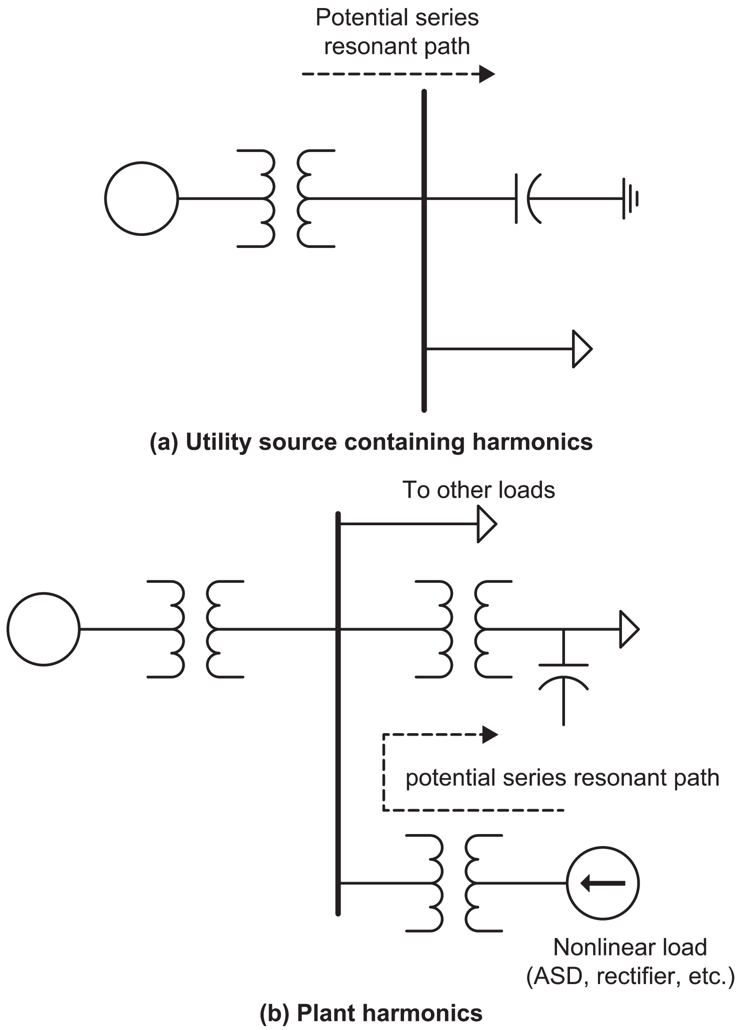


Figure 3—Potential series resonant situation

The equivalent impedance seen by the current source in Figure 4 is given by Equation (7). Note that at a particular frequency, $X_L = X_C$ and the denominator is reduced to R. This frequency is the resonant frequency and is given by Equation (4). The voltage across the complete circuit is given by Equation (8).

$$\overline{Z} = \frac{-jX_C(R + jX_L)}{R + j(X_L - X_C)} \tag{7}$$

$$\overline{V} = \overline{I}\,\overline{Z} \tag{8}$$

NOTE—Since $Z \gg X_L$ or X_C, V can be very high.[6]

[6]Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

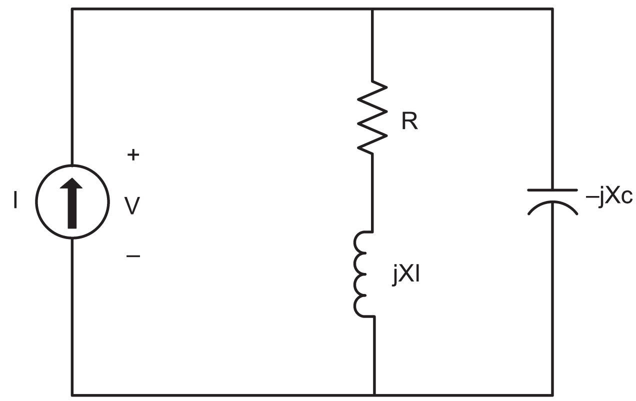


Figure 4—Typical parallel resonant circuit

In most cases, the resistance of power circuits is relatively small. It can be seen from Equation (7) that resonances can produce very large equivalent impedances at or near the resonant frequency, since R is generally small. Using the previous values ($R = 2\ \Omega$, $L = 3.98$ mH, and $C = 36.09\ \mu$F), a plot of the magnitude of the impedance in Equation (7) is shown in Figure 5. The sharpness of Figure 5 can be more conveniently calculated by the *current gain factor (ρ)* as the ratio of current in either the inductive branch or the capacitive branch to the injected current.

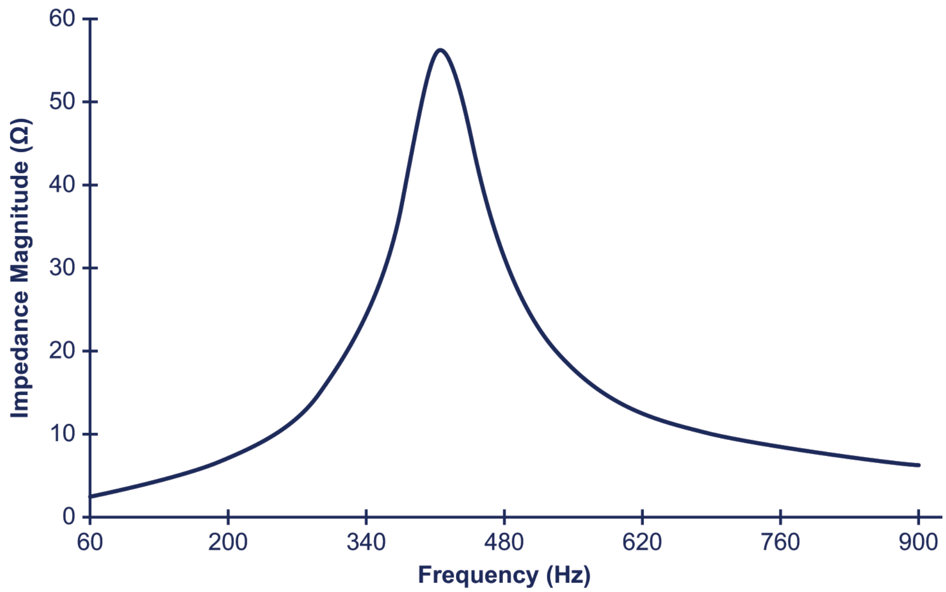


Figure 5—Impedance magnitude versus frequency for parallel circuits

One unique property of the parallel resonant circuit is that when excited from a current source at this frequency, a high circulating current will flow in the capacitance-inductance loop even though the source current is small in comparison. The current in the loop circuit is amplified to a level depending only upon the quality factor Q of the circuit. Q is proportional to the ratio of energy stored and energy dissipated per cycle in the circuit.

Parallel resonance can produce undesirable overvoltages. From Figure 5 and Equation (8), a current of 1.0 A at 60 Hz will produce a voltage of approximately 2.6 V across the capacitor (the net impedance being capacitive, $Z = 2.55$ @ 35.3°). However, the same 1.0 A current at 420 Hz (near the resonant frequency) will

produce approximately 55 V (the net impedance being inductive or close to resistive, $Z = 55.13 @ –10.8°$). This reasoning is often combined with known current injections for motor drives, rectifiers, etc., to predict potential harmonic overvoltages in power systems.

Parallel resonance typically involves the following:

a) The leakage inductance of large transformers and/or the equivalent inductance of the utility system.

b) The PF correction capacitors. Figure 6 shows a possible one-line for parallel resonance.

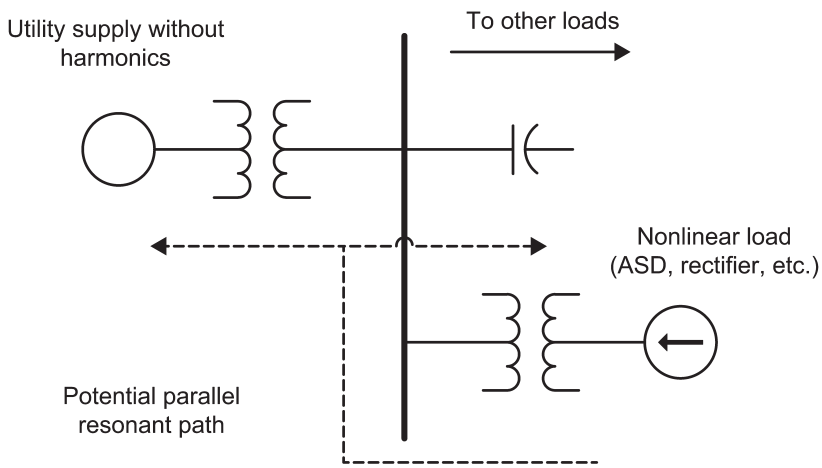


Figure 6—Possible parallel resonant circuit: plant harmonics

7.4.4 Resonances due to multiple filters

To illustrate the presence of multiple resonances, Figure 7 shows a plot of driving-point impedance as seen from a bus on which three tuned filters (5th, 7th, and 11th), a load, and the system impedance representing the utility are connected in parallel.

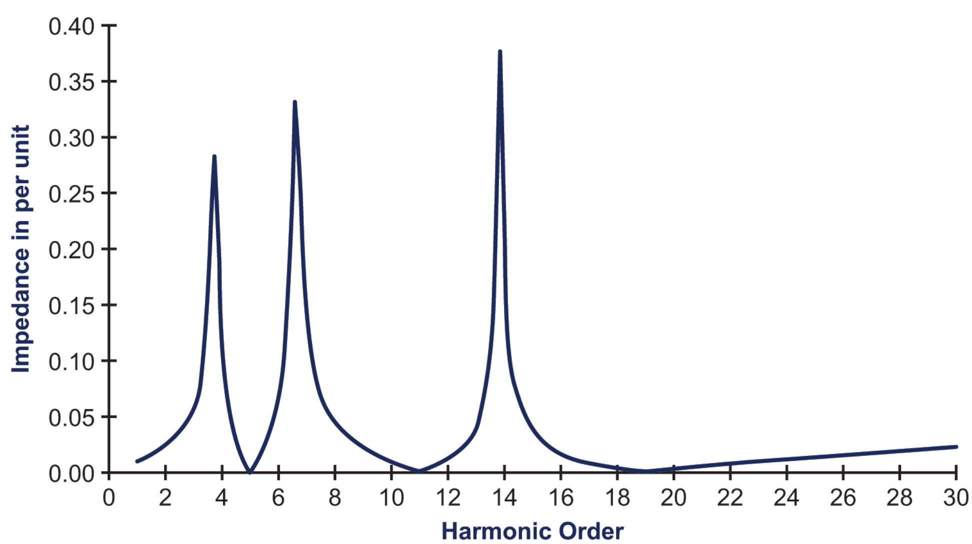


Figure 7—Impedance characteristic of multiple tuned filters

It can be seen that there are as many parallel resonance points as there are filters. The first parallel resonant frequency (near the 3rd) is due to system and load impedance, the second resonant frequency is due to the inductive part of the first filter (4.9th) and the capacitive part of the second filter (7th). Similarly, a third resonant frequency occurs between the 7th and 11th. Note that if the filters are tuned at odd harmonics (5th, 7th, 11th), the parallel resonance are likely to occur in between, often midway depending on the filter sizes.

7.5 Harmonic-analysis–related standards

In the United States, the Industry Applications Society (IAS) of the IEEE began a standards development project on harmonics in 1973. The first publication resulting from this project was IEEE Std 519-1981, entitled IEEE Guide to Harmonic Control in Electrical Power Systems. The IEEE publishes a hierarchy of Standards from the least to the most prescriptive, which are referred to as Guides, Recommended Practices, and Standards. In 1986, the Power Engineering Society (PES) joined the IAS to upgrade IEEE Std 519-1981 to the status of a Recommended Practice. In 1992, IEEE Std 519-1992, entitled IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, was published. In 2014, IEEE Std 519 was revised by the PES Transmission and Distribution Committee. It is widely used by the utilities and by industrial, commercial, and residential users in around the world. It has become the basis for all new power system designs and for the interface between the utilities and their customers.

The key prescriptions of IEEE Std 519-2014 are provided in Clause 5 (recommended harmonic limits). This clause addresses the harmonic current distortion and harmonic voltage distortion, respectively, and with maintaining the power quality by both the supplier and the user. The document also provides limits for notching and *IT* values for converter applications.

IEEE Std 519-2014 primarily deals with integer harmonics. It discusses interharmonic limits based on flicker in informative Annex A. IEEE Std 519 emphasizes the two following points in applying the harmonic indices: The Point of Common Coupling or PCC between the supplier and the user, and the ratio of the system short-circuit (SC) MVA and the maximum demand load MVA. The PCC is on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The SC ratio determines the total harmonic current distortion that can be injected into the system and allows higher limits for higher ratios. For current distortion limits, the fundamental current is calculated from the maximum demand load current, calculated over any 15-min or 30-min period and then averaged over the preceding 12-month period (if the data are available). Note that the actual fundamental current at any particular time is likely to be less than the maximum demand fundamental current; so the latter helps to reduce the THD percentage for any load less than the maximum demand load. However, this is not the general case, as actual harmonic current spectrums may vary based on the load currents.

A list of harmonic and power-quality-related IEEE standards can be found in Clause 2.

8. System simulation and modeling

8.1 General harmonic response study techniques

Harmonic analysis is required when a large number of nonlinear loads (typically greater than 25% to 30% of the total load on a bus or the system) are present or anticipated to be added, or the system has recorded power-quality issues. Often PF correction capacitor banks are added without due consideration of resonances, and a study may be required for corrective action. Frequent failure of power system components may also justify the undertaking of harmonic studies. The response of the system to harmonics can be studied by any of the following techniques:

a) *Hand calculation*s. Manual calculations are restricted to small-size networks since it is not only very tedious, but quite susceptible to errors.

b) *Field measurements*. Harmonic measurements are often used to determine the individual harmonic and Total Harmonic Distortion in the power system as part of the verification of the design, or compliance with a standard, or simply to diagnose a field problem. These measurements can be used to effectively identify harmonic issues at specific locations. However, it should be recognized that undertaking harmonic measurements in a systematic fashion can be expensive and time-consuming. Harmonic measurements reflect only the system conditions during which the measurements are taken, and do not necessarily represent the worst condition. Measurement errors due to inaccuracies of measuring instruments should be accounted for. Caution should be taken to avoid erroneous instrument utilization.

c) *Model calibration.* A well-defined test plan for measurements can provide baseline data and information to calibrate the system model. The calibration is critical since confirming that the model matches the actual system performance for various configurations or scenarios can add significant confidence that the model's simulated results for other configurations are valid.

d) *Computer simulation*. Computer simulation is the most convenient method, and perhaps a more economical way of analyzing the system. The advent of computer technology has made available quite sophisticated computer programs featuring a large array of system component models to be used in a variety of cases. Computer simulations are based on system-wide approaches utilizing the ideas of system impedance and/or admittance matrices, in conjunction with powerful numerical calculation techniques.

8.2 General power system element modeling for harmonic analysis

Correctly modeling each power system component and device is one of the key prerequisites in any computer simulation. In general, power system components and devices should be modeled using the following methods for harmonic analysis. More detailed models for individual components in industrial and commercial power system for harmonic-analysis studies are described in the following subsections. Table 1 gives a summary of modeling of various power system elements.

— Rotating machines are modeled by a winding resistance in series with a negative sequence impedance, both with frequency adjustments. Machine winding connections and grounding types need to be modeled.

— Passive loads are modeled by either parallel or series *RLC* impedance with frequency adjustments.

— Transmission line and cables are modeled by either short-line model (for a line or cable in a short length) or long-line model (for a line or cable in a long length). Both resistance and reactance of line and cable need to be adjusted by frequencies.

— Transformers are modeled by frequency-dependent resistance and reactance in series with magnetizing branch neglected in most cases. Transformer winding connections, grounding types, and phase shifts are modeled.

— Other system components are modeled with necessary frequency adjustments for resistive and inductive impedance.

However, it needs to be noted that the models used to represent the components in power systems should not be more complex than necessary to achieve reasonable answers.

8.3 Rotating machine model

In the context of the subject of this standard, rotating machines are not considered to be sources of harmonic currents, but rather are paths through which harmonic currents from nonlinear loads may circulate.

For induction machines, it is noted that at the higher harmonic orders, the harmonic slip approaches 1, and the resistance and inductance terms become constants. In practice, the harmonic slip can be considered 1 for harmonic orders greater than 9.

$$S_h \cong \frac{h \pm 1}{h} \tag{9}$$

In general, rotating machines are modeled by a series RL circuit with resistance and reactance adjusted to harmonic order h, refer to CIGRE CC-02 [B5], Arrilaga, Smith, Watson, and Wood [B3], and IEEE PES Task Force on Harmonic Modeling and Simulation [B43].

$$R_h = R\sqrt{h} \tag{10}$$

$$X_h = hX_2 \text{ or } X_h = \frac{\left(X_d'' + X_q''\right)}{2} \tag{11}$$

where

R is machine resistance derived from the machine power loss at fundamental frequency
X_2 is machine negative sequence reactance
X_d'' is d-axis subtransient
X_q'' is q-axis subtransient reactance

Table 1—Power system component models for harmonic analysis

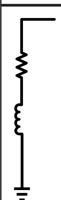
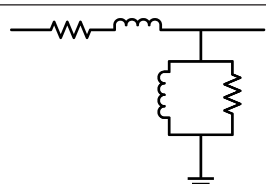
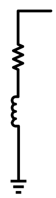
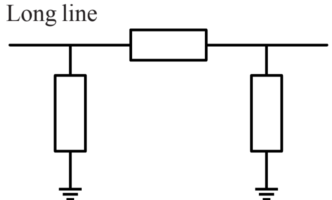
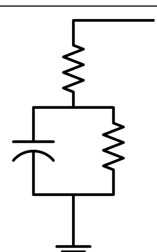
System components		Model parameters
Rotating machines		$R_h = R\sqrt{h}$, $X_h = hX_2$, or $X_h = \frac{\left(X_d'' + X_q''\right)}{2}$ R is machine resistance derived from the machine power loss at fundamental frequency X_2 , X_d'' , and X_q'' are machine negative sequence reactance, d-axis subtransient, and q-axis subtransient reactance, respectively
Transformer	 Shunt can be ignored if not a significant harmonic source	$R_h = R_T\sqrt{h}$ $X_h = hX_T$ R_T is derived from transformer power loss at fundamental frequency X_T is transformer short-circuit reactance

Table continues

Table 1—Power system component models for harmonic analysis *(continued)*

System components		Model parameters
Passive load		$R=\dfrac{V^2}{P} \quad X=\dfrac{V^2}{Q}$ $R_h = R\sqrt{h}$ $X_h = hX$ R and X are equivalent load resistance and reactance P and Q are active and reactive load on the bus
Line and cable	Short line:  Long line 	$R = R_{dc}\begin{cases}0.035M^2+0.938 & M<2.4\\ 0.35M+0.3 & M\geq 2.4\end{cases}$ $M = 0.05012\sqrt{\dfrac{f\mu_r}{R_{dc}}}$ f = frequency (Hz) R_{dc} = dc resistance (Ω/km) μ_r = relative permeability of the cylindrical wire ℓ = length (m) $z = r + \mathrm{j}x_L$ (Ω/m) $y = g + \mathrm{j}b_C$ (S/m) $Z_c = \sqrt{\dfrac{z}{y}}$ $\gamma_e = \sqrt{zy}$ $Z = Z_c \sinh(\gamma_e \ell)$ $\dfrac{Y}{2} = \dfrac{1}{Z_c}\tanh\left(\dfrac{\gamma_e}{2}\ell\right)$
Shunt capacitor		R_{loss} = equivalent loss resistance (Ω) $R_{discharge}$ = equivalent discharge resistance (Ω) X_c = capacitor impedance (Ω)

8.4 Transformer model

A transformer can be modeled as an ideal transformer in series with the nominal leakage impedance. The leakage reactance varies linearly with frequency, but proper resistance modeling must account for skin effect. Many variants for the transformer leakage impedance are recommended by CIGRE's "Harmonics, characteristic parameters, methods of study, estimates of existing values in the network." More complex models suggest considering magnetizing reactance, core loss, and the inter-turn and inter-winding transformer capacitances. Since the transformer resonance starts to occur at relatively high frequency, well above the 50th

harmonic, capacitances usually are ignored. The magnetizing branch, together with the core losses, are also neglected in most cases.

8.5 Passive load model

Various models have been proposed to represent individual loads and aggregate loads in harmonic studies. Specific models are available for individual loads, whether they are passive, rotating, solid-state, etc. An aggregate load is usually represented as a parallel/series combination of resistances and inductances, estimated from the fundamental frequency load power. This model can be used to represent an aggregate of passive loads (CIGRE JTF 36.05.02 [B5]).

$$R = \frac{V^2}{P} \quad X = \frac{V^2}{Q} \tag{12}$$

$$R_h = R\sqrt{h} \tag{13}$$

$$X_h = hX \tag{14}$$

where

R is the equivalent load resistance
X is the equivalent load reactance
P is the active load on the bus
Q is the reactive load on the bus

8.6 Transmission line and cable models

A short line or cable can be represented by a series *RL* circuit model. The resistance must be corrected to take into account the skin effect for higher frequencies. For longer lines, modeling of the line shunt capacitance becomes necessary. Both the lumped parameter model (equivalent p model for example) and the distributed parameter model are used, but the latter is better suited to represent the line's response over a wide frequency range. The distributed line model can be approximated by cascading several lumped parameter models. Cascading sections of either model to represent a long line is worthwhile to produce a harmonic voltage profile along the line.

The variation of line resistance due to skin effect can be evaluated using the following expression (IEEE Task Force on Harmonics Modeling and Simulation [B44]; Smith and Ran [B61]):

$$R = R_{dc}\begin{cases} 0.035M^2 + 0.938 & M < 2.4 \\ 0.35M + 0.3 & M \geq 2.4 \end{cases} \tag{15}$$

$$M = 0.05012\sqrt{\frac{f\mu_\gamma}{R_{dc}}} \tag{16}$$

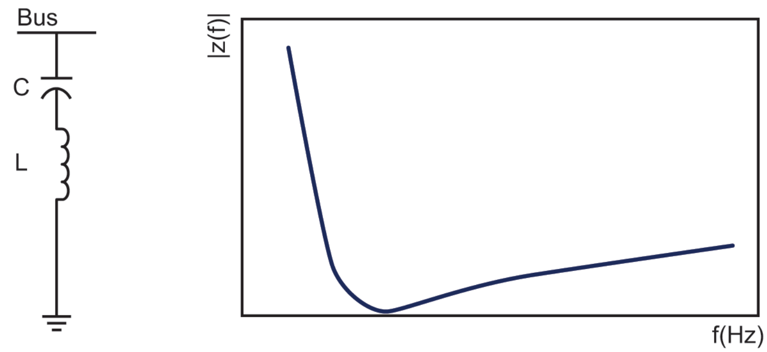
where

f is frequency in Hz
R_{dc} is in Ω/km

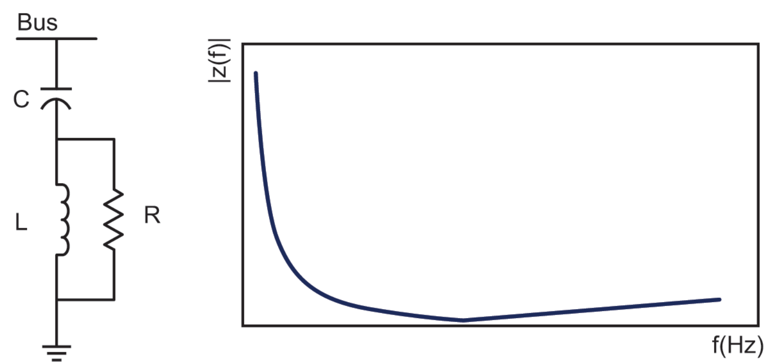
8.7 Filter models

Filters, by definition, exhibit small impedances at tuned frequencies. At the fundamental frequency, their impedance is capacitive; thereby supplying reactive power to the electrical network. Many types of filters are applied in power systems for different purposes. Filters most commonly used for harmonic mitigation are illustrated in Figure 8 along with their characteristics (note that in part (a), single-tuned filter, resistance is assumed small enough that the minima of the plot is almost zero). A single-tuned filter is used to suppress a specific harmonic at or near the tuned frequency. High-pass filters can be of first, second, or third order. The second-order filter is often used to suppress higher frequencies. A more recent type of high-pass filter, a *C-type filter*, is becoming popular due to its smaller losses at the fundamental frequency.

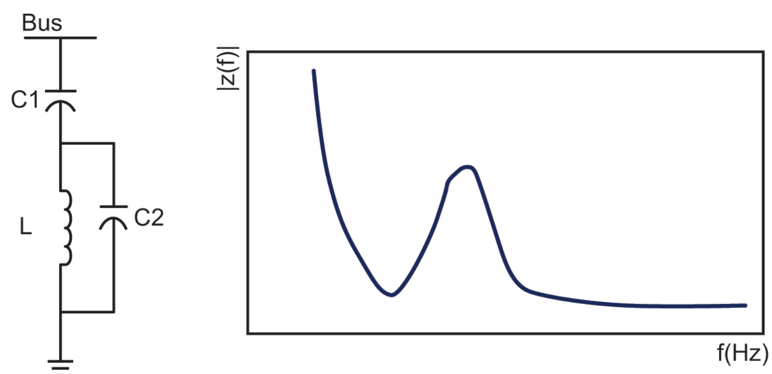
Application of filters is one of the commonly employed solutions to limit the effects of harmonics. Other remedial measures—such as moving the disturbing loads to higher voltage levels, reinforcing the system, changing capacitor sizes, and adding tuning reactors to capacitor banks—are also used. In any case, economics will dictate the most appropriate solution. Recent studies advocate the utilization of active filtering in an effort to counter the injected harmonics close to the source, but primarily in low-voltage systems.



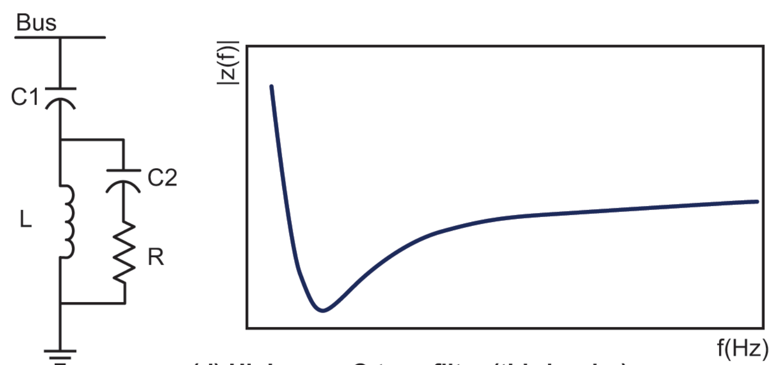
(a) Single-tuned filter



(b) High-pass filter (second order)



(c) Undamped high-pass filter (third order)



(d) High-pass C-type filter (third order)

Figure 8—Filters commonly used for harmonic mitigation

8.8 PF correction capacitor model and its effect

PF correction capacitors are applied in most systems to help achieve lower cost operation. It is important to consider variations in the frequency response due to the size of PF capacitors. For a sample case, a power factor–correcting capacitor bank is to be connected to a 33 kV bus that has a load on a 33 kV to 6.6 kV transformer. To simplify the situation and make a point, assume in this example that the 33 kV to 6.6 kV transformer and the 6.6 kV bus are disconnected. The utility fault MVA is constant at 4000 MVA, $X/R = 20.0$ (@ 60 Hz). The system can be represented by an equivalent utility inductive impedance in parallel with the capacitor bank as shown in Figure 9. Figure 10 shows the variations in the driving point impedance, which is the impedance at a node, at the 33 kV bus as a function of capacitor bank size. The parallel resonant frequency is determined by the equivalent inductive MVA and capacitor Mvar at the node:

$$h = \sqrt{\frac{\text{Mvar}}{\text{MVA}}}$$

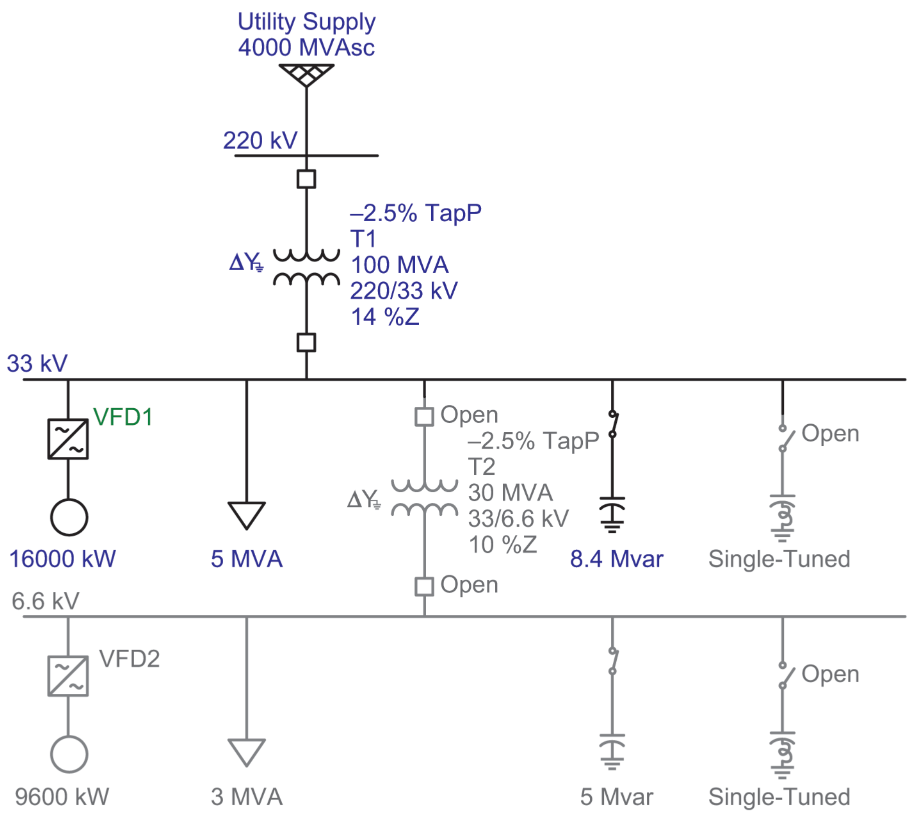


Figure 9—Example system for PF correction capacitor model

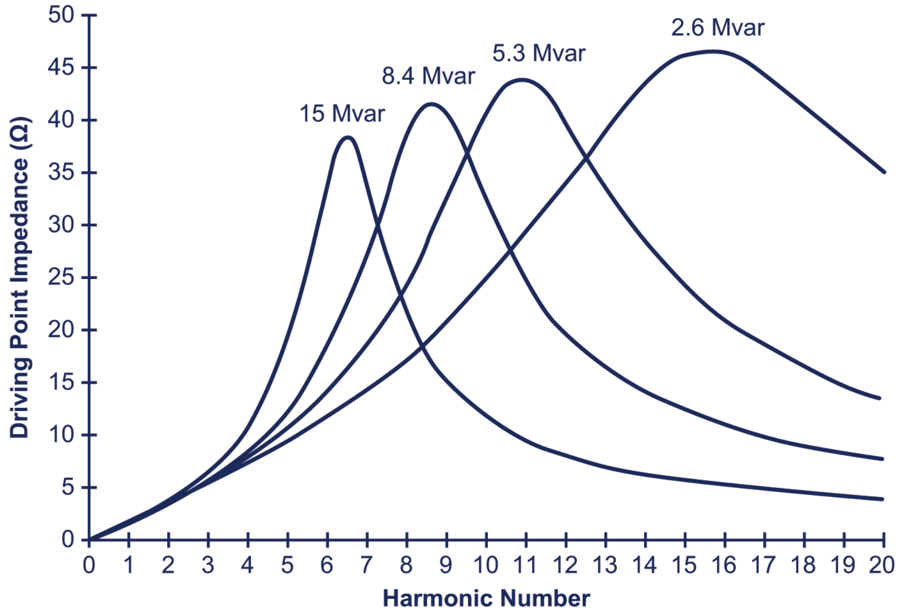


Figure 10—Variations in frequency response at the 33 kV bus as a function of capacitor bank size

The plots reveal, first, that resonant frequency decreases as capacitor bank size (and therefore power factor) increases, and second, that peak resonant impedance increases as capacitor bank size (and therefore power factor) decreases. It should be noted that the tendency of resistive damping to increase with frequency often lessens the effect of increasing resonant impedance.

8.9 Representation of the utility system

It is important to consider the effects of variations of the utility supply fault MVA on the frequency response of the industrial system. Figure 11 shows a portion of the frequency scan results for the example system in IEEE Std 399. The utility fault MVA is varied from its minimum (4000 MVA) to its maximum (10 000 MVA) with the system X/R (@ 60 Hz) held constant at 20.0. The plots show the general trend of an increase in resonant frequency as the utility fault MVA increases. The conclusion is that industrial systems connected to very strong utility supplies (high fault MVA) are less likely to encounter problematic resonance conditions at low frequencies.

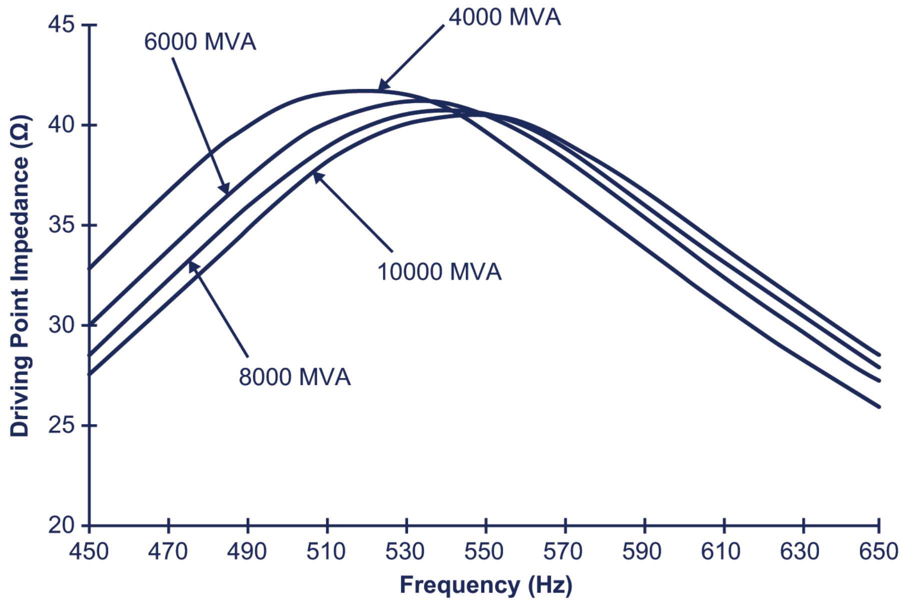


Figure 11—Frequency response at the 33 kV bus as a function of utility fault MVA

8.10 Computer simulation methods

To conduct harmonic-analysis studies, power system network models, harmonic source models, and models for each individual system component models need to be defined. A proper simulation method also needs to be selected.

There are two basic modeling and simulation methods to represent harmonic generation from nonlinear devices in power systems.

The first method is harmonic power flow method. This method models harmonic generation from nonlinear power system devices by injecting harmonic voltages and/or currents from these nonlinear devices into the power network. To determine the harmonic voltages and harmonic currents generated by the nonlinear devices, techniques such as Fast Fourier Transformation (FFT) can be employed to extract data from the total voltage and current waveforms. Harmonic voltage source and current source are expressed in a series of harmonics with both magnitude and initial phase angle specific for each harmonic component. The magnitude of the harmonic component is usually in percentage of the fundamental quantity, and the phase angle is either in degrees or radians. The power transmission or distribution system is modeled as an electrical impedance network in nodal voltage equations similar to the load flow studies. Each network element is represented by a set of linear equations corresponding to its previously described circuit model in Table 1. Reactance and admittance of the element circuit model have to be adjusted for the harmonic order or frequency when harmonic sources are applied to the network at the same harmonic order of frequency.

$$\begin{bmatrix} Y_{11} & -Y_{12} & \dots & -Y_{1n} \\ -Y_{12} & Y_{22} & \dots & -Y_{2n} \\ & \dots & & \\ -Y_{1n} & -Y_{2n} & \dots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \dots \\ V_N \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \dots \\ I_n \end{bmatrix} \tag{17}$$

Depending on the network component frequency characteristics, sometimes the frequency saturation effect needs to be taken into consideration when adjusting their impedance. Due to the sequence characteristics of harmonics, in general all three sequence impedance networks—namely positive sequence network, negative

sequence network, and zero sequence network—need to be formulated and used accordingly with harmonic sources at different orders. One important part in formulating a zero sequence network is to make sure the data for machine and transformer winding connection types and grounding configurations are included, because they will affect the zero sequence network. With harmonic sources determined and modeled, and network selected and adjusted to the harmonic orders, harmonic currents are injected into the network from harmonic current sources and harmonic voltages are applied to the buses where harmonic voltage sources exist. By solving Equation (17) at each frequency, we obtain the nodal voltages. This computation is performed for each harmonic frequency of interest. From the harmonic voltages we can compute the harmonic currents in each branch:

$$I_{ij} = \left(V_i - V_j\right) \times Y_{ij} \tag{18}$$

Next, overall bus voltages and branch currents are obtained by synthesizing from their fundamental values plus harmonic components. The overall bus voltages and branch currents can be expressed in different forms, such as total rms value, maximum or peak value, etc.

The inverse of the nodal admittance matrix is called the *nodal impedance matrix*. This matrix is rich in quantitative information. The diagonal entry on the *i*th row is the Thevenin impedance of the network seen from bus *i*. By computing values of this matrix over a range of frequencies, we obtain the frequency response of the network seen from each bus. Exact resonance frequencies can be determined from this computation. The off-diagonal values in the matrix show the effect of a harmonic current injection on the bus voltages. Consider a single harmonic source connected at bus *i* forcing 1.0 A of current into the network. The harmonic voltage at bus *j* is simply Z_{ij}, the value found in the *i*th row and *j*th column of the nodal impedance matrix. The harmonic voltage at bus *j* due to numerous sources can be solved by superposition.

More detail description of power-flow type harmonic-analysis method can be found in chapter 7 of IEEE Power Engineering Society's "Tutorial on harmonics modeling and simulation" [B27].

The second method is directly based on nonlinear device voltage-current characteristics and uses an iterative approach. This method requires that a voltage-current characteristic curve is given for each nonlinear device in the system. Starting from an initial condition, current or voltage outputs from nonlinear devices are generated based on their curves. Since these current or voltage outputs are based on assumed initial conditions, adjustments to the initial condition are needed based on the first approximation results. Usually several iterations will be needed before reaching accurate outputs from these nonlinear devices. The final outputs will be distorted waveforms of a sinusoidal wave, containing harmonic components. Fourier decomposition technique can be applied to the distorted current or voltage waveforms to extract the harmonic contents. With accurate harmonic contents in currents or voltages from the nonlinear devices determined, network analysis techniques are then applied to solve overall system voltages and currents and their level of distortions due to harmonics generated by the nonlinear devices.

Alternatively, time-domain analysis programs, such as EMTP can be used, where the nonlinear device characteristics are used in conjunction with a network impedance model to create the simulated distorted waveforms, which are then decomposed using Fourier analysis.

8.11 Common harmonic distortion indices

The Total Harmonic Distortion, the rms value, the Telephone Interference Factor, and related factors are readily computed from the harmonic voltage or current (U_n) and the fundamental frequency (U_1) quantities as follows:

Total Harmonic Distortion (THD):

$$THD = 100 \times \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \tag{19}$$

where

n is the harmonic order and usually the summation is made starting from the fundamental ($n = 1$) up to the 50th harmonic order
U designates either voltage or current

Individual Harmonic Distortion (IHD):

$$IHD = 100 \times \frac{U_n}{U_1} \tag{20}$$

where

n is the harmonic order and usually the summation is made up to the 50th harmonic order
U designates either voltage or current

rms value:

$$U_{rms} = \sqrt{\sum_{n=1}^{\infty} U_n^2} \tag{21}$$

where

n is the harmonic order and usually the summation is made starting from the fundamental ($n = 1$) up to the 50th harmonic order
U designates either voltage or current

Telephone interference magnitude:

$$UT = \sqrt{\sum_{n=0}^{\infty} (K_n \times P_n \times U_n)^2} \tag{22}$$

where

n is the harmonic order
K_n is a weighting factor related to hearing sensitivity (IEEE Std 519)
P_n is a weighting factor related to hearing sensitivity (IEEE Std 519)
U designates either voltage or current
UT is used for Telephone Interference Factor (TIF) calculation

Telephone Interference Factor (TIF):

$$TIF = \frac{\sqrt{\sum_{n=0}^{\infty} (K_n \times P_n \times U_n)^2}}{U} \tag{23}$$

where

n is the harmonic order
K_n is a weighting factor related to hearing sensitivity (IEEE Std 519)
P_n is a weighting factor related to hearing sensitivity (IEEE Std 519)
U designates either voltage or current

These useful quantities summarize the harmonic analysis into a few quality-related factors.

In harmonic analysis, two impedance calculations are made to study the system characteristics for series and parallel resonances. These are driving point and transfer impedances. The driving point impedance is defined as voltage, calculated at a node *i*, due to current injected at the same node, in other words:

$$Z_{ii} = \frac{V_i}{I_i} \tag{24}$$

Since this is the "net" impedance of all circuits seen from that bus, it provides useful information regarding resonances. By changing the existing circuits (location of capacitors, cables, etc.) or the design of planned filters, the driving point impedance, and hence resonance, can be changed. The concept of transfer impedance is similar to the driving point impedance, in that it is defined as the voltage measured at one bus due to current injected at another bus. In other words:

$$Z_{ij} = \frac{V_i}{I_j} \tag{25}$$

where

Z_{ij} is the transfer impedance to bus *i*
V_i is the voltage measured at bus *i*
I_j is the current injected at bus *j*

The transfer impedance is useful for evaluating harmonic voltages at any location other than the bus where the current is injected.

8.12 Harmonic generation

A harmonic flow study requires the knowledge of harmonics generated by nonlinear devices. Depending on the nature of the device and accuracy required, this can be a task by itself. Very often, typical values are used for most industrial studies. This subject has been dealt with well in IEEE Std 519 and also in Chapters 3 and 4 of Prabhakara, Smith, and Stratford's *Industrial and Commercial Power Systems Handbook*, therefore a detailed treatment is unnecessary here.

Table 2 is provided here, however, for a 6-pulse and multipulse converter as a matter of comparison, and to demonstrate how certain characteristic harmonics can be canceled by phase multiplication. Harmonics generated by a 6-pulse converter for a square wave are well-known (IEEE Std 519). The magnitude of the harmonic current is given by

$$I_h = \frac{I_1}{h} \tag{26}$$

where

I_1 is the fundament current
h is the harmonic order given by $h = mp \pm 1$

where

m is an integer
p is the number of pulse

Table 2 indicates that for a 12-pulse converter, the 5th harmonic and 7th harmonic are canceled in the ideal case. However, due to system and equipment imbalances (non-ideal behavior), a perfect cancellation does not occur, and in general the current is assumed to be 10% to 15% of what would be expected (Prabhakara, Smith, and Stratford). For example, for a 12-pulse converter, the 5th harmonic would be around 2% instead of 20%.

Figure 12 (a) and (b) show the conceptual arrangement of 12-pulse and 24-pulse converters using 3-phase, 2-winding transformers. In Figure 12 (a), the two rectifier transformers are individually phase-shifted by 30° with respect to each other. When viewed from Bus A and when they are both equally loaded, they collectively appear to be a 6-phase, 12-pulse system. Similarly in Figure 12 (b), Bus C and Bus D appear to have 6-phase, 12-pulse rectification but, due to differing connections of the power transformer, the system becomes a 12-phase, 24-pulse system viewed from Bus B. This configuration will greatly reduce all generated harmonics below the 23rd, compared to 6-pulse systems. The models for higher-order converters used here assume a multiple phase-shifting transformer array, which supplies the individual rectifiers. In cases where specialized transformers are used to generate phase shifts, the results may be different. In addition, higher-order converters are extremely susceptible to supply voltage unbalance, which may result in considerably higher than expected harmonic currents.

The typical harmonic spectra shown here are for conventional current source thyristor phase-controlled rectifiers. When voltage source converters, pulse-width modulation, and other technology are used, the expected harmonics may be as much as two times those for conventional rectifiers.

Table 2—Characteristic ac line harmonic currents in multipulse systems

Harmonic	Rectifier system pulse number				Harmonic frequency	Harmonic current in percent of fundamental	
	6	12	18	24		Theoretical	Typical
5	X				300	20.00	19.20
7	X				420	14.20	13.20
11	X	X			660	9.09	7.30
13	X	X			780	7.69	5.70
17	X		X		1020	5.88	3.50
19	X		X		1140	5.26	2.70
23	X	X		X	1380	4.36	2.00
25	X	X		X	1500	4.00	1.60
29	X				1740	3.45	1.40
31	X				1860	3.23	1.20
35	X	X	X		2100	2.86	1.10
37	X	X	X		2220	2.70	1.00
41	X				2460	2.44	0.90
43	X				2580	2.33	0.80

Table continues

Table 2—Characteristic ac line harmonic currents in multipulse systems *(continued)*

Harmonic	Rectifier system pulse number				Harmonic frequency	Harmonic current in percent of fundamental	
	6	12	18	24		Theoretical	Typical
47	X	X		X	2820	2.13	0.80
49	X	X		X	2940	2.04	0.70

NOTE—The theoretical values are given for a 6-pulse converter with ideal characteristics (i.e., square current waves with 120° conduction). The last column gives typical values based on a commutating impedance of 0.12 pu and a firing angle of 30° and infinite dc reactor. These values are on the basis of one 6-pulse converter or all converters, assuming that the harmonics are additive. Since some harmonics will be canceled, but not entirely, a small percentage value may be assumed, as explained earlier in this subclause. Note that if the dc reactor is not large, some of the harmonics can be greater than typical (or theoretical) and some smaller.

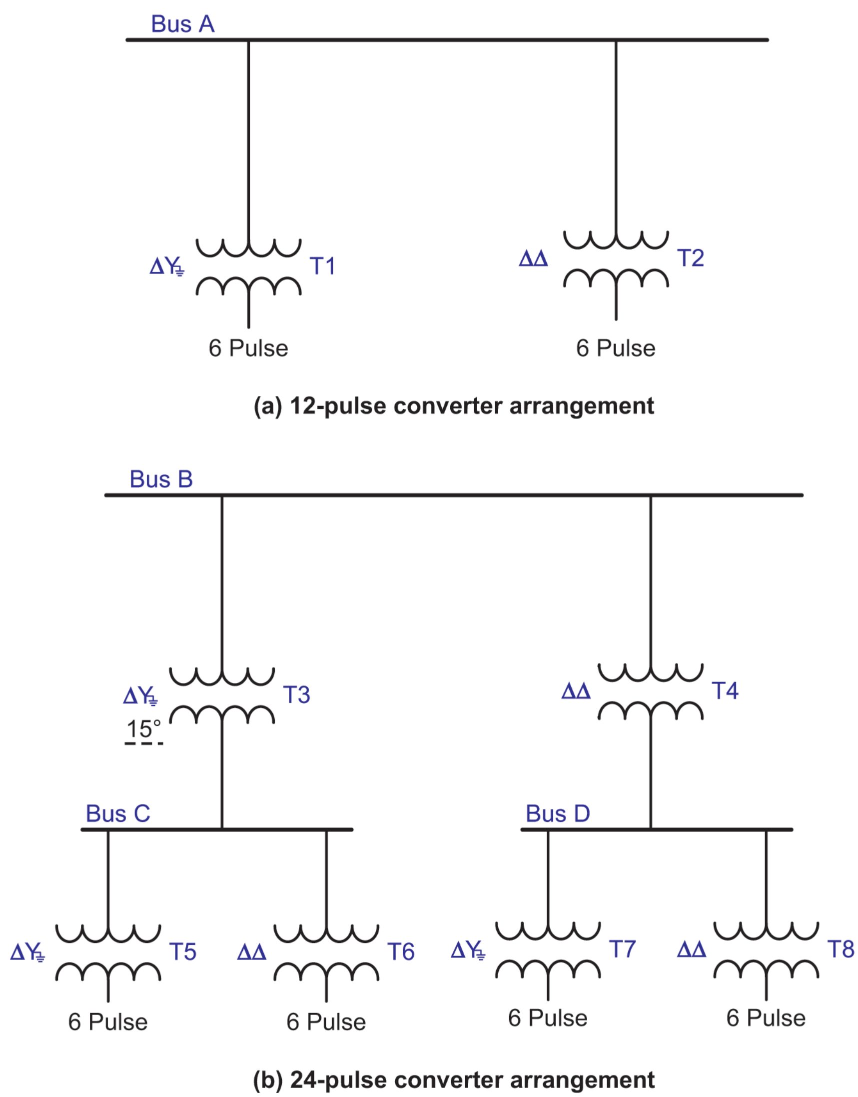


Figure 12—Multipulse converter arrangements

8.13 Interharmonics

Some devices and equipment in power systems can generate voltages and/or currents that contain components that are non-integer multipliers to the fundamental frequency. These components are called interharmonics. Devices and situations that can result in interharmonics in industrial and commercial power systems are cycloconverters, adjustable speed drives (ASDs)/variable frequency drives (VFDs), arc furnaces, and loads that do not pulsate synchronously with the fundamental power system frequency, etc.

Interharmonics generated from these devices and situations can be expressed in Equation (27):

$$f_i = \left(mp_1 \pm 1\right) f_n \pm np_2 f_z \tag{27}$$

where

f_i is the system fundamental frequency
f_z is the modulation frequency that is converter/ASD output, or load fluctuation frequency
p_1 is the converter/ASD rectifier number of pulse
p_2 is the converter/ASD inverter number of pulse
m is 0, 1, 2, 3…
n is 1, 2, 3…

Phase sequence of interharmonics requires special attention to determine, because they are important in harmonic power flow studies. Details on interharmonics, their origin, phase sequence, and special issues in harmonic analysis are found in references (Hang, Xu, and Liu, [B18]; IEEE Task Force on Harmonics Modeling and Simulation [B43]; Smith and Ran [B61]; Yacamini [B65]).

The example shown in Figure 13 simulates the effect of an interharmonic source. Considering the interharmonic source effect, voltage waveform at BUS B clearly shows harmonic distortion; whereas if the interharmonic source is ignored, the voltage waveform will hardly present harmonic distortion.

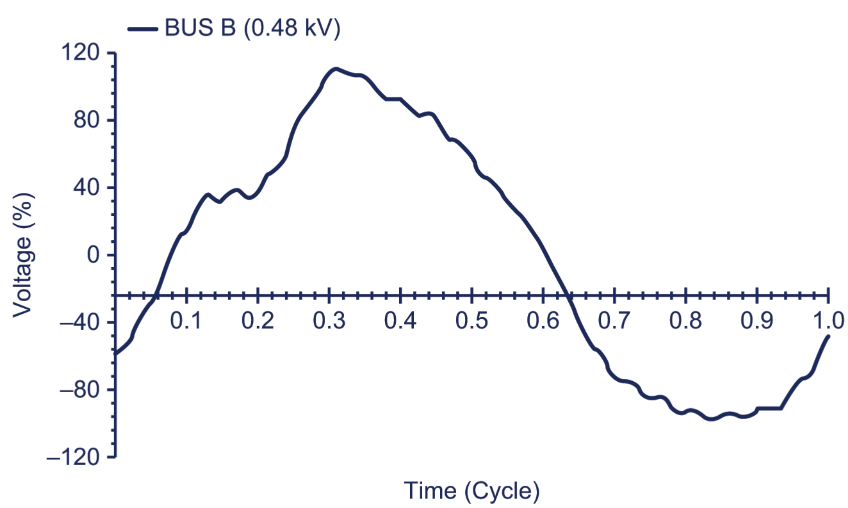


Figure 13—Study results with consideration of interharmonics (voltage waveform at BUS B)

If interharmonics are not considered, calculated TIF at BUS B would be 75.1% and harmonic distortions at voltage waveform would be missed as shown in Figure 14.

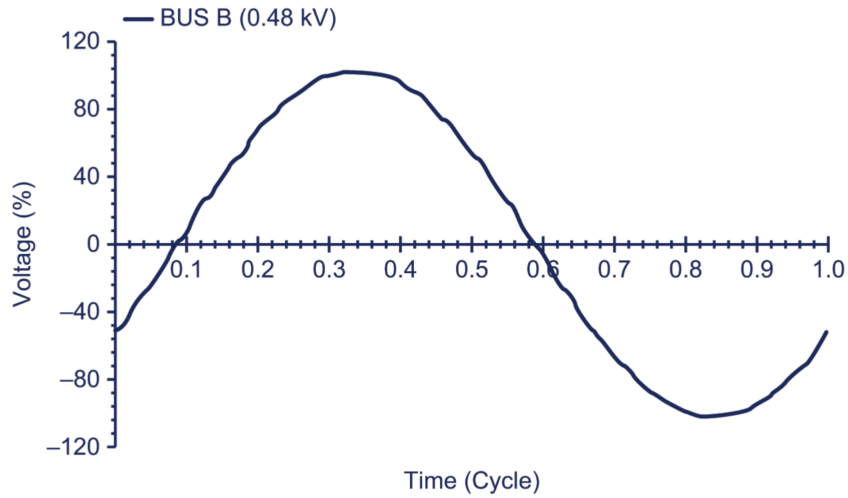


Figure 14—Study results without consideration of interharmonics (voltage waveform at BUS B)

Interharmonics can cause light flicker, overload of conventional series tuned filters, overload of outlet strip filters, and CT saturation.

8.14 Harmonic analysis for industrial and commercial systems

The purpose of a harmonic study was discussed in Clause 6. The following summarizes the steps normally required for a harmonic study in the industrial and commercial environment:

a) Prepare a system one-line diagram. Note that it is important to include capacitor banks and long lines and cables within the industrial system or the utility system near the Point of Common Coupling (PCC).

b) Gather equipment data and ratings (see Clause 10).

c) Obtain the locations of nonlinear loads and the generated harmonic currents.

d) Obtain from the utility company the relevant data and harmonic requirements at the PCC. These include the following:

    1) Minimum and maximum fault levels, or preferably system impedances, as a function of frequency for different system conditions.

    2) Permissible limits on harmonics including distortion factors and *I*-*T* factor. The criteria and limits vary considerably from country to country. Typical values for different system voltages are given in IEEE Std 519.

e) Carry out harmonic analysis for the base system configuration by calculating the driving point impedance loci at the harmonic source buses as well as at all shunt capacitor locations.

f) Compute individual and total harmonic voltage and current distortion factors and *I*-*T* values (if required) at the Point of Common Coupling.

g) Examine the results and, eventually, go back to step a) or step c), depending on whether the network data or only the parameters of the analysis need to be modified.

h) Compare the composite (fundamental plus harmonic) loading requirements of shunt capacitor banks with the maximum rating permitted by the standards. IEEE Std 18™ has defined the following operating limits:

— Continuous operating voltage ≤ 110% of the rated voltage

— rms crest voltage ≤ 1.2 times the rated rms voltage

— kvar ≤ 135% of the rated kvar

— Current ≤ 180% of the rated rms currents

i) Relocate the capacitors or change the bank ratings if they are found to exceed their ratings. Apply a detuning reactor if a resonance condition is found. Go back to step e). Note that adding a tuning reactor will increase the fundamental voltage on the capacitor and may also increase harmonic voltage. The capacitor duty must be satisfied as given in step h).

j) Add filters if the harmonic distortion factors and *I-T* values at the PCC exceed the limit imposed by the utility.

The above steps should be carried out for the base system configuration as well as for system topologies resulting from likely contingencies. Any future system expansion and utility short-circuit level changes should also be considered.

Harmonic filtering using passive filters is one of the most convenient and practical methods for harmonic distortion mitigation. Selecting and designing harmonic filters often begins with a preliminary filter design, generally based on past experience, and then refined, as the harmonic performance indices are calculated. In this process of refinement, several steps are involved that determine the number of filters, effective reactive power compensation, and performance indices. Other factors, such as filter switching and protection, loss of one or more filter banks, and space requirements should also be considered. One rather obvious design objective is to use as few filters as possible and compare the performance with no filter. Filter location is another consideration. Effective filtering will probably require that the filters be located near harmonic sources. However, economics may dictate that filters be located at higher voltage levels (near the PCC or main bus) to meet the demands of all harmonic sources.

Generally, the filters are tuned at one of the dominant odd characteristic harmonics starting from the lowest order (which in most cases are 5, 7, 11...). In some cases the lowest order may be 2 or 3, as in arc furnace applications. Ideally, the filters should be tuned to the exact harmonic order, i.e., 5, 7, 11, etc. However, the practical considerations may require that it is safer to tune slightly below the nominal frequency. If it is necessary to offset the parallel resonance frequency, the filter may be intentionally tuned below, or in exceptional cases above the nominal frequency. For example, a 5th harmonic filter may cause a resonance near the 3rd, and it would be desirable to tune it slightly below or above the 5th to offset the resonance at 3rd. Another example is one in which the resonant frequency is very close to the 5th (say at 4.7) for very sharp filters. In this case it will be desirable to tune it below the 5th so that tolerances and temperature deviations, etc., will not let the resonant frequency coincide with the 5th harmonic injection frequency.

The two main components of passive filters, capacitors and reactors, are discussed here. The nominal fundamental kvar rating of the capacitors determines the effectiveness of harmonic filtering. Therefore an initial estimate of the capacitor kvar is very important. The larger the bank size, the easier it is to meet a given harmonic performance criteria. Besides the harmonic requirements, the following additional design factors may need to be considered:

— The system power factor (displacement power factor) may be corrected to required or desirable value (usually above 0.9).

— The total kVA demand on the supply transformer may have to be reduced if the transformer is overloaded.

— Similarly, the current ratings of buses and cables may have to be reduced.

As a general rule, the capacitor needs to be derated in order to absorb the additional duty from the harmonics (a derating factor of 15% to 20% in voltage would be desirable). Note that because of the derating, the kvar would be reduced by the square of the factor. The loss of kvars is, however, somewhat compensated by the cancellation of the capacitive reactance by the inductive reactance of the filter. The effect of this cancellation is to increase the capacitor voltage (above the bus voltage) by the following factor:

$$c = \frac{h^2}{h^2 - 1} \text{ pu of the fundamental} \tag{28}$$

where

h is the harmonic order

For the conventional single-tuned filter this factor is calculated in Table 3.

Table 3—Fundamental voltage across a single-tuned filter capacitor

Harmonic order	3rd	5th	7th	11th	13th
Per-unit voltage	1.125	1.049	1.021	1.008	1.005

Once the harmonic study is completed and the filter selection has been made, the capacitor rating with respect to voltage, current, and kvar should be checked. All these three ratings need to be satisfied independently according to IEEE Std 18. Filter designers could either satisfy these requirements themselves if standard units are used, or request capacitor suppliers to meet these requirements if special units are used.

Either an air-core or iron-core reactor may be used depending upon the size and cost of the reactor. In general, the iron-core reactors are limited to 13.8 kV. Air-core reactors are available for the complete range of low-voltage, medium-voltage, and high-voltage applications. The iron-cored reactors will save space and provide the advantage of being enclosed in indoor or outdoor housing along with capacitors and other control and protection components as required.

The reactors need to be rated for the maximum fundamental current and the worst generated harmonics for the worst system configuration. Also, the reactor vendor needs to calculate all the losses, fundamental and harmonic, core losses in case of the iron-cored reactors, and stray losses due to frequency effects so that the hot-spot temperatures are within the allowable dielectric temperature.

One big unknown factor during the filter design is the Q factor, or the ratio of the inductive reactance to resistance at the tuned frequency. This is usually estimated based on experience. However, if during the study it is felt that Q is not critical, then the reactor should be specified to have the natural Q (the Q of the reactor that is naturally obtained with no special design consideration or cost). On the other hand, if the low-Q reactor would help to mitigate amplifications near parallel resonance frequencies, then a low-Q reactor should be specified. Manufacturers have a high tolerance on Q (as much as 20%), and this should be recognized. Note also that the low Q design will produce higher losses.

9. Required data

9.1 Data for analysis

The following data are required for a typical industrial and commercial power system harmonic-analysis study:

a) A single-line diagram of the power system to be studied.

b) Specific system configurations.

c) Maximum expected voltage for the system supplying the nonlinear loads.

d) Bus nominal voltage, load adjustment factors, and voltage and current harmonic distortion limits for both total harmonics and individual harmonic.

e) Utility connecting point, three-phase and single-phase short-circuit MVA and *X/R* ratio or positive, negative, and zero sequence resistance and reactance. The existing harmonic voltage spectrum of the utility system (external to the system being modeled). If the utility exhibits varying harmonic impedance at different frequencies, then a complete impedance spectrum needs to be obtained.

f) Rated MVA/kVA, rated voltage, negative reactance at fundamental frequency, resistance, operating mode (swing, voltage control, var control of P-Q load), winding connection and grounding type, and generation for generators. If the generator is considered as a harmonic source due to saturation, then a harmonic spectrum should also be obtained.

g) Rated MVA/kVA/HP, rated voltage, negative reactance at fundamental frequency, resistance, winding connection and ground type, and loading of motors. If limitations exist, motors on a given bus can be lumped together into one composite motor with equivalent ratings and parameters.

h) Transmission line and cable, length, positive, negative, and zero sequence resistance, reactance and admittance of unit length, and any special frequency characteristics of resistive, inductive, and capacitive impedance. The units can be either in per-unit or percent values, or ohmic values, depending on the software used or preference. Also, rated voltage of the circuit in which the circuit element is located.

i) Positive, negative, and zero sequence reactance and resistance, and frequency characteristics of resistance and reactance of bus duct, current limiting reactors, and other circuit elements. The units can be either in per-unit or percent values, or ohmic values, depending on the software used or preference. Also, rated voltage of the circuit in which the circuit element is located.

j) MVA/kVA rating, rated voltages, percent positive, negative and zero sequence impedance and *X/R* ratio, MVA/kVA rating, and three-phase connection and grounding types of power transformers. If the transformer harmonics due to in-rush or saturation are to be considered, then harmonic spectrum.

k) The three-phase connections, kvar, and unit kV ratings of shunt capacitors and shunt reactors.

l) Passive load ID, bus connection, rated MVA/kVA, rated voltage, initial loading, phase connection and grounding type, and frequency characteristics of resistive, inductive, and capacitive loads.

m) Nameplate ratings, number of phases, pulses, and converter connections. Actual manufacturer's test sheets on each converter transformer are also helpful, but not absolutely mandatory. If this information is not readily available, the kVA rating of the converter transformer may be used for establishing the harmonic current spectrum being injected into the system. Most importantly, converter's harmonic characteristics or harmonic spectrum including harmonic type (voltage or current), harmonic magnitudes, and phase angles.

n) For arc furnace installations, secondary lead impedance from the transformer to the electrodes plus a loading cycle to include arc megawatts, secondary voltages, secondary current furnace transformer taps, and transformer connections.

o) Harmonic filter type and structure, resistance, reactance, and capacitance for all elements, maximum voltage for capacitors, and maximum currents for inductor.

p) Harmonic limits for special buses (PCC, dedicated, critical, etc.) in Total Harmonic Distortion as well as in individual harmonic.

10. Data collection and preparation

System modeling and data collection are vital to harmonic analysis. The following typical procedures are recommended for different types of system device, equipment, and entireties to prepare data for computer modeling and harmonic-analysis studies.

a) Power grid data should be from the utility.

b) Rotating machine data should be based on machine manufacturer-provided data sheet and nameplate, plus any data from available factory acceptance test, site acceptance test, and/or commissioning test.

c) Load data should be from the load name plate plus any testing data.

d) Line and cable data should be from the manufacturer-provided data sheet plus any testing data.

e) Transformer data should be based on nameplate plus any testing data.

f) Other power system component data should be based on manufacturer-provided data sheet and nameplate, plus any testing data.

g) Nonlinear device voltage-current characteristics should be based on manufacturer-provided data sheet plus any special test data.

h) Harmonic filter data should be based on manufacturer data sheet plus any testing data.

i) Voltage and current harmonic spectrum data should be provided by the manufacturer plus any filed testing data.

11. Model and data validation

After the system modeling and data entry are done, it is still important to validate the model performance using some benchmark or legitimate results. Guidelines listed can be followed for this purpose:

a) The complete system model, including network model, load model, machine model, harmonic filter model, and harmonic source model should be validated before performing any harmonic studies.

b) The model validation process consists of fundamental load flow validation and harmonic source validation.

c) The fundamental power flow should be validated against a base case power flow that should be validated by collected measurement data, online measurements, or other methods specified in IEEE Std 399 for load flow analysis.

d) Harmonic source model should be validated by field measurements. Independent validation should be tried for each harmonic source to avoid interaction between different harmonic sources.

e) If it is possible, verification of bus voltage distortions and circuit current distortions simulated by the system model and harmonic sources should be arranged using field measurement data.

f) Measurements must be used to verify the system model prior to the performance of a detailed harmonic-analysis study. This is especially desirable for arc furnace installations. In order to ensure that harmonic measurements will produce reliable results, careful consideration must be given to both test equipment and procedures being applied; see Shipp, “Harmonic analysis and suppression for electrical systems supplying static power converters and other nonlinear loads.” The test results may identify the cause of a harmonic problem so that the need for a detailed harmonic study is either eliminated or the study is simplified.

12. Study scenarios

After the system model is completed, required data are entered, and both are verified and validated, the next step is to define and create study scenarios for harmonic-analysis studies. The following are some recommendations for this task.

a) Each study scenario should include system configuration to define system connections and topology, data revision to specify electrical parameters for the network and machines, harmonic filter locations, types, and parameters. For harmonic power flow studies, additional information is to be specified, including fundamental power flow loading category to specify system load, fundamental generation category to specify generator (power grid) mode, power generation and controlled voltage, harmonic library to specify harmonic source data, and other study-scenario–specific solution-related parameters. For harmonic frequency scans, the range for scan frequency and the step of frequency increase are to be specified.

b) Points of interest including bus voltage harmonic (individual and total harmonic) distortion, branch current harmonic (individual and total harmonic) distortion, and bus driving point impedance (for identifying parallel resonance purpose) should be specified so that plots and reports can be generated from the study.

c) Study scenarios should include study cases covering all possible system configurations, operating conditions, as well as harmonic sources to generate system harmonic distortion information for power-quality assessment. Study scenarios should also investigate parallel oscillation conditions under all possible system configurations and operating conditions.

d) Additional study scenarios can be added to the scenario base when it is necessary.

e) Study scenarios and solutions should be saved for future retrieval or modification.

13. Solution parameters

In addition to system configuration, data revisions, operational requirements and constraints, harmonic sources, and other important variables specified for each study scenario, there are some solution-related parameters that should also be defined.

The solution-related parameters may include, but are not limited to:

a) Fundamental load flow method and precision

b) Initial bus voltage magnitude and phase angle for fundamental load flow

c) Report, plot, and results display options

d) Modeling method; for example, short-line or long-line model for transmission lines and cables

e) If a frequency scan study is to be performed, frequency scan step and range should be specified as well

Solutions parameters are used to ensure a calculation study is executed under and for a specific condition.

14. Results and report

14.1 Introduction

Calculation results can be presented in different formats, including study report, study plots, and one-line display.

14.2 Study report

The harmonic study report should contain the following essential data and information about the studied system:

a) System overall information such as number of buses, number of branches and branch types, number of machines, etc.

b) Solution parameters including engineering data revision, system configuration, etc.

c) Information on other original system input data, configuration, scenario, and solution parameter information

d) Bus input data including bus name or ID, bus nominal voltage, bus generation and bus loading, and bus voltage harmonic distortion limit, if there are any

e) Harmonic source spectrum including both magnitude and phase angle, and location (connected device or bus)

f) Full fundamental load flow report

g) Bus voltage total THD and individual IHD violations, if there are any

h) Other harmonic indices for bus voltage and current including rms, peak (crest), *TIF* for bus voltages and branch currents, and $I \times T$ for branch currents

i) Transformer, cable, capacitor, and filter overloading report, if there are any

j) Identified parallel oscillation location, bus driving-impedance magnitude, and frequency from harmonic frequency scan study

k) Tabulated report for harmonic voltage at each harmonic frequency for selected buses

l) Tabulated report for harmonic current at each harmonic frequency for selected branches

14.3 Study plot

Harmonic study results can be effectively represented using plots and graphs. The most popular and useful harmonic study plots include:

a) Graphic plots for bus voltage harmonic spectrum and waveform, and branch current harmonic spectrum and waveform. These are also from harmonic load flow study.

b) Graphic plots for bus driving point impedance magnitude and angle versus frequency or harmonic order from harmonic frequency scan study.

Figure 15, Figure 16, Figure 17, and Figure 18 show sample plots for harmonic current spectrum within selected harmonic range, and current waveform during one cycle, bus driving point positive impedance magnitude and phase angle.

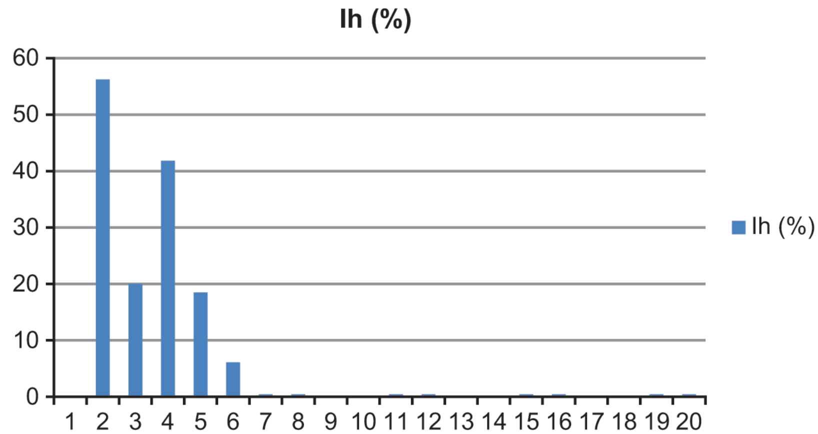


Figure 15—Harmonic current spectrum in percent of fundamental current (horizontal axis is harmonic order)

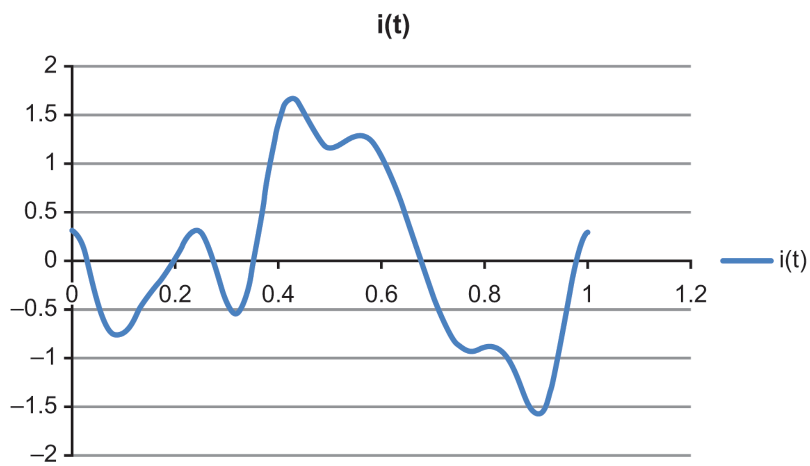


Figure 16—Current waveform with harmonics in one cycle (vertical axis is in per unit and horizontal axis is in cycle)

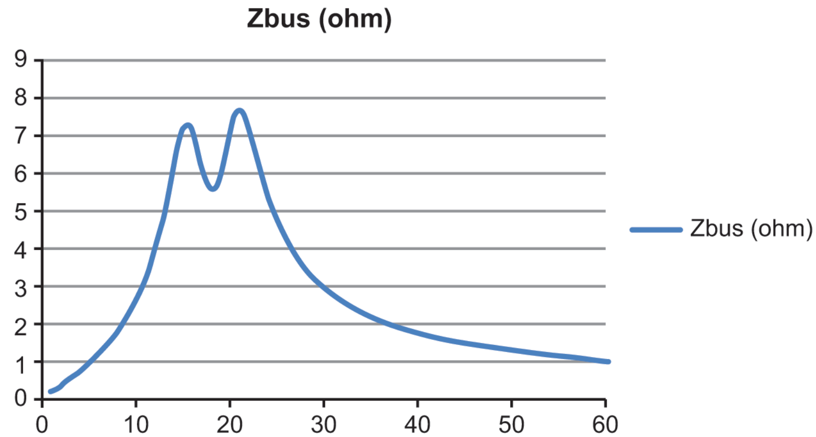


Figure 17—Bus driving point impedance magnitude within a selected frequency range (horizontal axis is multiplier of the fundamental frequency 60 Hz)

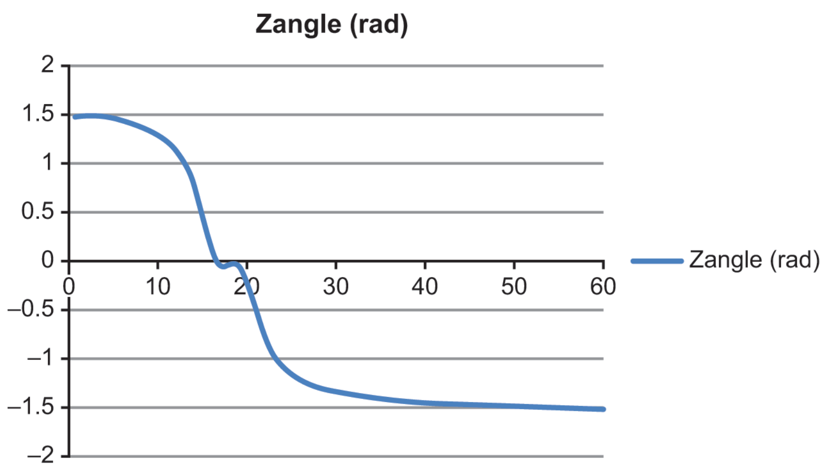


Figure 18—Bus driving point impedance phase angle within a selected frequency range (horizontal axis is multiplier of the fundamental frequency 60 Hz)

14.4 Study display

Visual displays of harmonic study on one-line diagrams are desired to provide overview of the system situation under the study scenario. Fundamental information displayed on the one-line diagram should include, but not be limited to the following quantities:

a) System fundamental load flow results (bus voltages, branch currents, generations, and loads, etc.).

b) Total Harmonic Distortion (THD) for user-selected buses and branches.

c) Bus voltage harmonics in absolute values as well as in percent of fundamental voltage for user-selected buses.

d) Branch current harmonics in absolute values as well as in percent of fundamental current for user-selected branches.

e) Capacitor bank peak (crest) voltages.

f) Harmonic filter fundamental and harmonic currents and voltages.

g) Bus and branch voltage and current total rms values for user-selected elements.

h) Branch Telephone Interference Factor (TIF) for user-selected branch elements.

Figure 19 shows sample one-line display from harmonic load flow study, bus total rms voltages, and branch total rms currents. Bus total voltage harmonic distortions and branch total current harmonic distortions (THD) are shown in red.

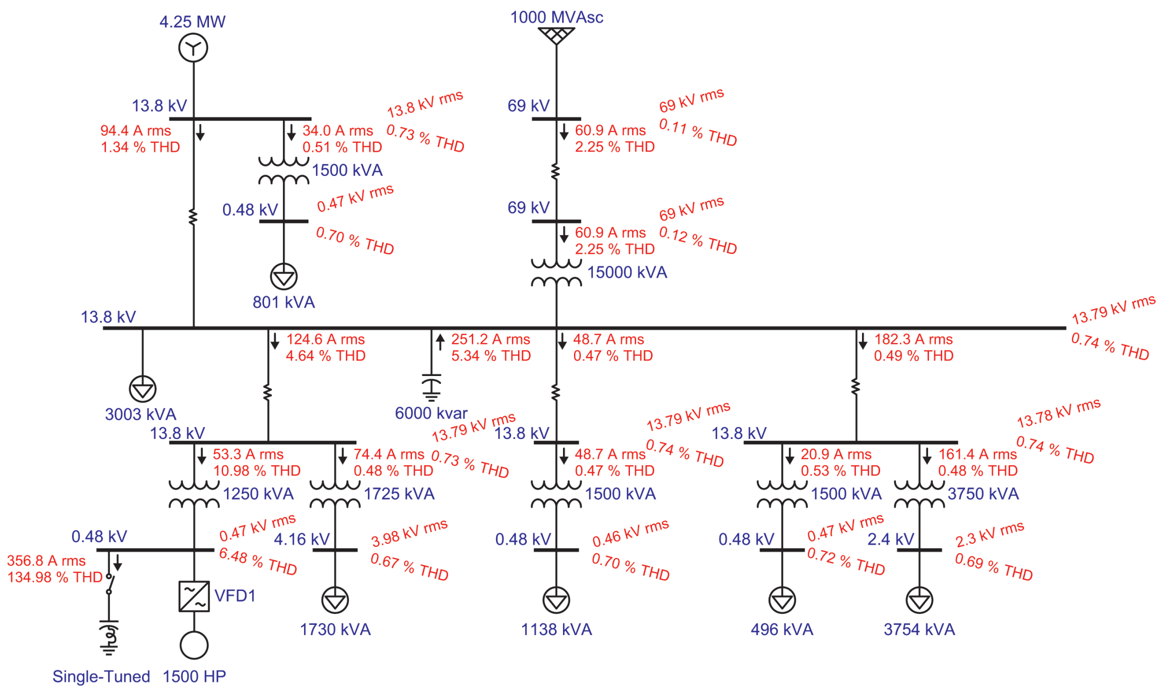


Figure 19—Sample one-line display of results for harmonic power flow calculation

14.5 Harmonic study distortion limits

When performing harmonic studies using any power system analysis software, it is necessary to determine if the total voltage and current harmonic distortion exceed the limits allowed at the Point of Common Coupling (PCC). The limits vary according to the regional regulating authority and are a function of the distribution voltage and the available short-circuit current at the PCC. A good starting reference point to determine if allowable limits are exceeded is to use IEEE Std 519. The recommended harmonic current distortion limits used by IEEE Std 519 is shown in Table 4, and the voltage distortion limits are shown in Table 5.

Table 4—Maximum odd harmonic current distortion limit in percent of load current (I_L)

For distribution systems (120 V through 69 000 V)						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table continues

Table 4—Maximum odd harmonic current distortion limit in percent of load current (I_L) *(continued)*

For distribution systems (120 V through 69 000 V)						
For sub-transmission systems (69 001 V through 161 kV)						
I_{sc}/I_L	**$3 \leq h < 11$**	**$11 \leq h < 17$**	**$17 \leq h < 23$**	**$23 \leq h < 35$**	**$35 \leq h \leq 50$**	**TDD**
< 20	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0
For transmission systems (> 161 kV)						
I_{sc}/I_L	**$3 \leq h < 11$**	**$11 \leq h < 17$**	**$17 \leq h < 23$**	**$23 \leq h < 35$**	**$35 \leq h \leq 50$**	**TDD**
< 25	1.0	0.5	0.38	0.15	0.1	1.5
25 < 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

where

I_{SC}/I_L is the ratio of short-circuit current available at the Point of Common Coupling (PCC) to the maximum fundamental load current

Table 5—Harmonic voltage distortion limit

Bus voltage at PCC	Individual Voltage Distortion (IVD) (%)	Total Harmonic Distortion (THD) (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161.001 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is a high-voltage direct current (HVDC) terminal whose effects will have attenuated at points in the network where future users may be connected.

The limits recommended in this practice are intended for application at a PCC between the system owner or operator and a user, where the PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the high-voltage (HV) side of the transformer. For commercial users (office parks, shopping malls, etc.) supplied through a common service transformer, the PCC is commonly at the low-voltage (LV) side of the service transformer, and this would be the most applicable case for the scope of this standard. For international users, IEC 61000-3-6 provides similar distortion limits for commercial and light industrial applications.

Most commercially-available power system analysis packages include the capability of comparing the THD and Total Design Distortion (TDD) to distortion limits and generate alerts in the event of abnormal loading condition. Most commonly generated alerts include bus Voltage Total Harmonic Distortion (VTHD), Voltage Individual Harmonic Distortion (VIHD), filter overloading, capacitor overvoltage, cable overcurrent, and parallel resonance. IEEE Std 18 can be used as reference to set the maximum withstand overvoltage and overcurrent limits for shunt power capacitors while performing harmonic simulation.

14.6 Harmonic study result analyzer

A harmonic study result analyzer allows viewing the results of various harmonic studies in one table so that users can analyze and compare the results of different studies in one glance.

For harmonic power flow analysis, comparison and analysis of results of individual output reports is time consuming, especially for large systems when the least and highest harmonic distortion results need to be identified. It is more practical to use comparison tools that allow analyzing multiple simulation results. Tools of this nature can provide a numerical comparison at all harmonic levels and orders for every bus, branch, and load in the system. In addition, these tools can help to identify the best-case and the worst-case results among all cases studied. Table 6 shows an example of Voltage Total Harmonic Distortion (VTHD) results for buses obtained from multiple studies, Study-1, Study-2, and Study-3.

Table 6—Harmonic result analyzer indicating VTHD results of multiple studies

Bus ID	Nominal kV	Allowable (%)	Study-1 (min. load) (%)	Study-2 (norm. load) (%)	Study-3 (max. load) (%)
UPS A	0.48	1.5	1.430	*1.470*	**1.560**
UPS B	0.48	1.5	1.400	*1.440*	**1.530**
Bus A	13.8	1	0.196	0.198	0.207
Bus B	13.8	1	0.408	0.419	0.450
Server loads	0.12	10	**11.270**	**11.200**	**11.060**

In Table 6, critical VTHDs are highlighted in bold for values greater than the acceptable range, and marginal VTHDs are highlighted in italic for values greater than 95% of the acceptable percentage. The results also show how VTHDs vary under different loading conditions, i.e., minimum loading (90%), normal loading (100%) and maximum loading (110%). This visual comparison of results can help to understand general behaviors of system voltage and current harmonic distortions.

Such analysis/comparison tools can provide many benefits, including reduction of time and cost to conduct harmonic comparisons, and elimination of the human errors introduced by comparing results manually. IEEE recommended solutions can also be facilitated by using such comparison tools.

15. Features of analysis tools

With the advancement of computer modeling methods and numerical simulation techniques for harmonic analysis in industrial and commercial power system, many desired features for harmonic analysis are now available from computer simulation tools. Some key features of computer simulation tools for harmonic analysis are listed below.

Modeling harmonic sources with ease:

— Model both voltage and current harmonic and interharmonic sources.

— Allow users to define voltage and current harmonic and interharmonic source in spectrum format. Spectrum can include both harmonic magnitude and phase angle at any frequencies.

— Allow users to define harmonic sources by specifying standard rectifier, converter, and inverter parameters, such as number of pulse, firing angle, extinction angle, commutation reactance, dedicated transformer taps, etc.

— Allow users to add and save harmonic and interharmonic source data into a harmonic library that can be linked to a harmonic generation element in a system model used for studies.

Network modeling capabilities:

- Model any size power system with common elements.
- Model different types of elements using standard harmonic models.
- Allow users to define system configurations (system connectivity).
- Correctly consider and handle machines, transformers, and load-winding connections and group types.
- Accept and consider element positive, negative, and zero-sequence impedance.

Analysis method features:

- Perform harmonic power flow studies and calculate all standard and common harmonic and interharmonic indices, including bus voltage individual and Total Harmonic Distortion, bus voltage total rms value, bus voltage peak value, branch current individual and Total Harmonic Distortion, branch current total rms value, branch current peak value, branch current telephone interference, branch current *I-T* product, etc.
- Produce bus voltage and branch current time domain waveforms.
- Perform frequency scan within the specified frequency range using specified frequency step, and generate bus driving point impedance plots.
- Provide a harmonic result analyzer to view the results of various harmonic studies in a glance.

Tools should also have harmonic filter modeling and turning capabilities:

- Model common harmonic filters, including by-pass filter, high-pass damped filter, high-pass undamped filter, single-tuned filter, third order damped filter, third order C-type filter, etc.
- Automatically size harmonic filters based on tuning frequency, harmonic current at the tuning frequency, power factor compensation requirement, minimization of cost, and other user-specified objectives and constraints.
- Verify filter tuning frequency and harmonic distortion suppressions by either harmonic power flow simulation, harmonic frequency scan simulation, or both.

Output result capabilities:

- Plot selected elements by users with different plot types, including bus voltage spectrum chart, bus voltage time domain waveform, branch current spectrum chart, branch current time domain waveform, and bus driving point impedance magnitude and phase angle frequency response.
- Export plot data to other commercial databases.
- Report both summarized and detailed data for input data (bus, machine, load, branch, protective device, harmonic filter, harmonic library, and harmonic sources, etc.), output results (network fundamental load flow results, harmonic load flow results, bus driving point impedance by frequency scan results), tabulated plot data, etc.
- Support popular document formats including Word, Excel, PDF, Crystal Report, etc.
- Display simulation results directly on one-line diagrams.
- Allow users to view results on one-line diagram by selecting a particular frequency including fundamental frequency and a harmonic frequency.

16. Illustration examples

16.1 Introduction

Several applications of harmonic studies are presented in this clause. Frequency scans, capacitor effects, and filter design are demonstrated. Example 1 is a simplified industrial plant, Example 2 is an IEEE harmonic working group test case, and Example 3 is a full industrial complex model.

16.2 Example 1: A simplified industrial system

16.2.1 Single-line diagram and data for sample system 1

The diagram in Figure 20 is representative of a simplified industrial power system. It includes multiple voltage levels and PF correction capacitors. The data required for basic harmonic studies are provided in Table 7, Table 8, and Table 9.

The capacitor banks have been sized to provide a power factor of approximately 0.95 lagging at the low-voltage side of each transformer and may consist of series and parallel units.

16.2.2 Case Study 1: Diode rectifier on 33 kV bus

The impact of a proposed ASD motor at the 33 kV bus are to be determined. The switches connecting the 33 kV to 6.6 kV transformer are open in this case study; therefore, the 6.6 kV bus is not considered for this case (refer to 16.2.3 for Case Study 2, where the switch is considered closed). The ASD is a harmonic source. The example has been shown to illustrate harmonic issues to use a 12-pulse drive at the 33 kV bus.

A frequency scan is performed at the 33 kV bus, and the resultant driving point impedance is shown in Figure 20. Note the distinct impedance peak (indicating a resonant point) near the 9th harmonic (540 Hz). Also note that an isolating transformer is considered to be internal to VFD 1 (ASD) in Figure 20.

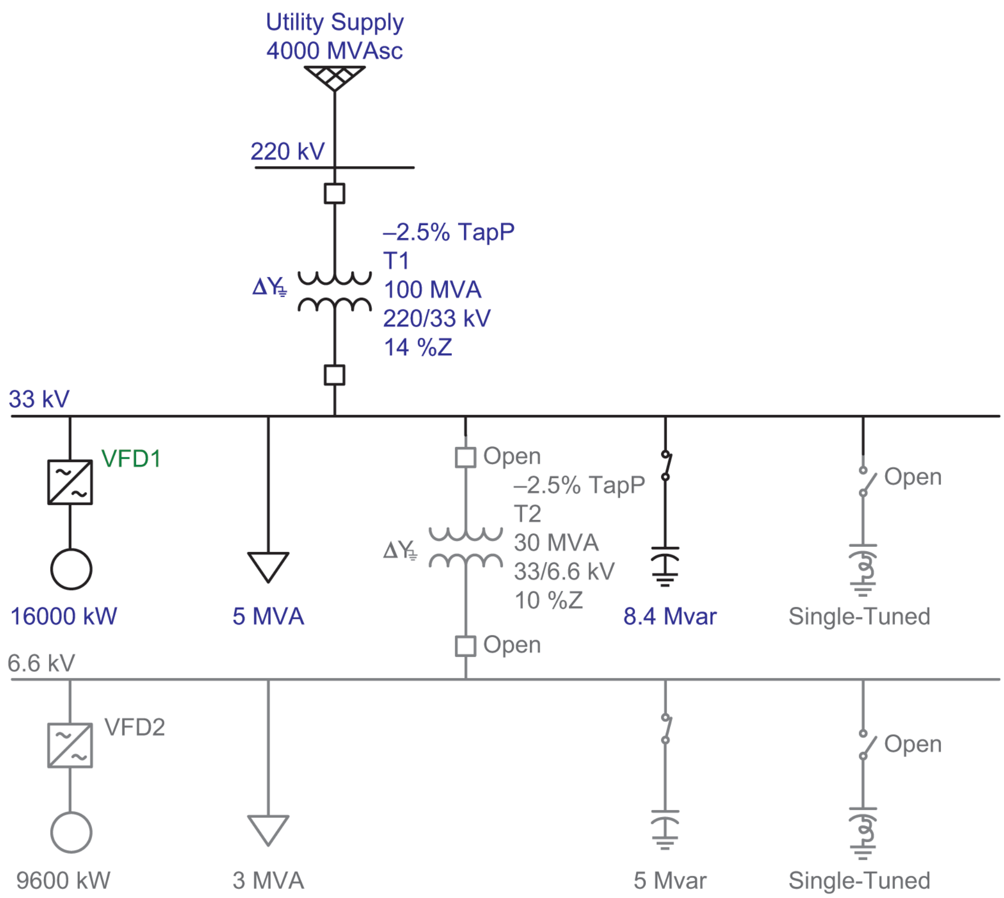


Figure 20—Example system for harmonic studies

Table 7—Utility supply data

Parameter	Value
Supply voltage	220 kV
Short-circuit capacity	4000 MVA
X/*R*	20.0

Table 8—Transformer data

Parameter	T_1	T_2
Power rating (MVA)	100	30
Voltage rating (kV)	220 to 33	33 to 6.6
Impedance (%)	14	10
X/*R*	10.0	10.0

Table 9—Load and capacitor data

33 kV bus	Linear load	5 MVA @ 0.8 lag
	ASD load	16 MW
	Capacitor	8.4 Mvar

Table continues

Table 9—Load and capacitor data *(continued)*

6.6 kV bus	Linear load	3 MVA @ 0.8 lag
	ASD load	9.6 MW
	Capacitor	5 Mvar

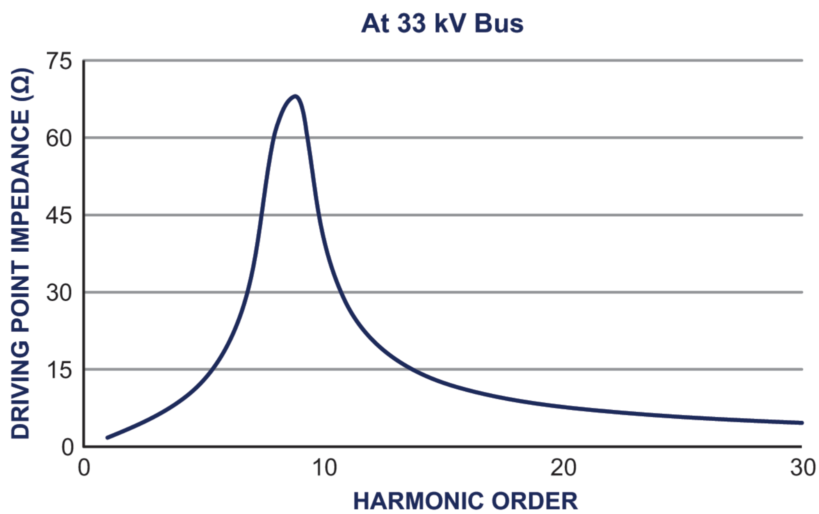


Figure 21—Driving point impedance at the 33 kV bus

The impacts of this resonance condition are determined using a frequency scan solution. The harmonic content of the diode rectifier current (on the ac side) is given in Table 10. Figure 22 and Figure 23 show the voltage harmonic magnitude spectra at the 33 kV and 220 kV buses with percent THD, respectively.

Table 10—Harmonic content of diode rectifier current (ac side) at the 33 kV bus

Harmonic order	Frequency (Hz)	Magnitude (A)
1	60	271.7
23	1380	10.97
25	1500	9.93
47	2820	4.05
49	2940	3.76

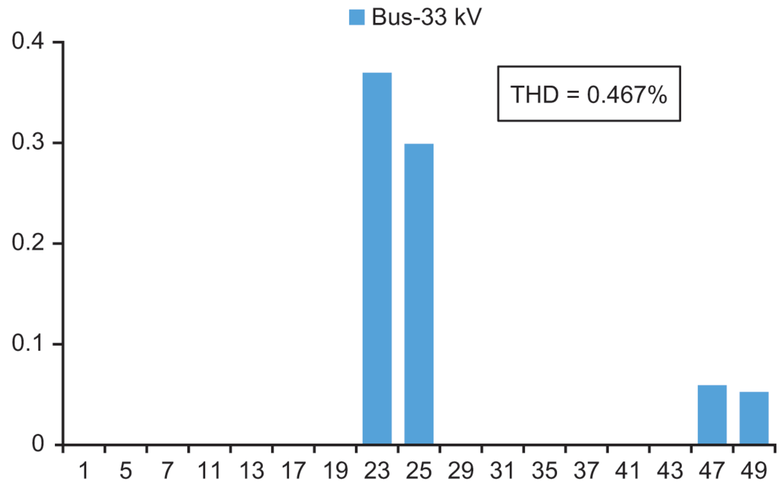


Figure 22—Harmonic magnitude spectrum at the 33 kV bus

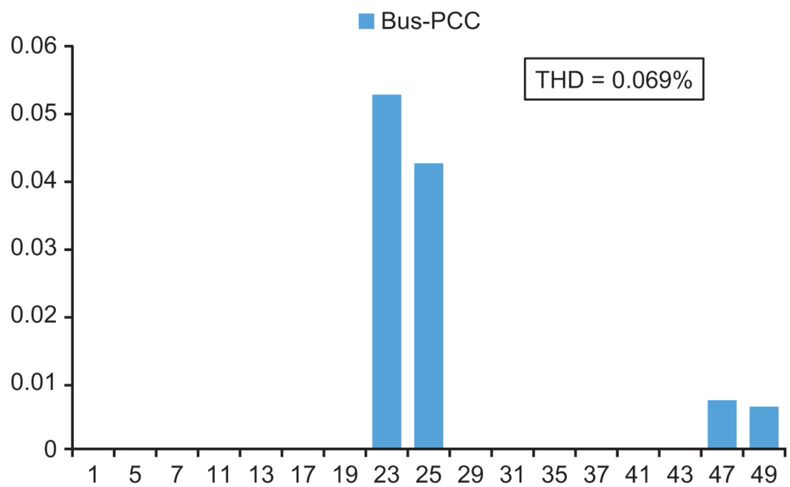


Figure 23—Harmonic magnitude spectrum at the 220 kV bus

16.2.3 Case Study 2: Effects of including the 6.6 kV bus

This study is identical to that of 16.2.2 except that the switches to the 33 kV to 6.6 kV transformer are closed, resulting in the connection of the 6.6 kV bus to the system. A frequency scan is again conducted at the 33 kV bus, and the resultant driving point impedance is shown in Figure 24. In addition, a frequency scan is conducted at the 6.6 kV bus to obtain the resultant driving point impedance plot in Figure 25.

Note the presence of two resonance points. This is to be expected because there is typically the same number of resonance points as the number of capacitors.

The impacts of the resonance points on voltage waveforms are shown in Table 11 where the diode rectifier load on the 33 kV bus is given in 16.2.2. Harmonic content and approximate voltage THD values are given for the 6.6 kV, 33 kV, and 220 kV buses. Relative to the case in 16.2.2, the voltage distortion comparison of THD between two cases are:

THD = 0.467% for case in 16.2.2, and increases to 2.13% in 16.2.3, at the 33 kV bus level

THD = 0.069% for case in 16.2.2, and increases to 0.333% in 16.2.3, at the 220 kV bus level

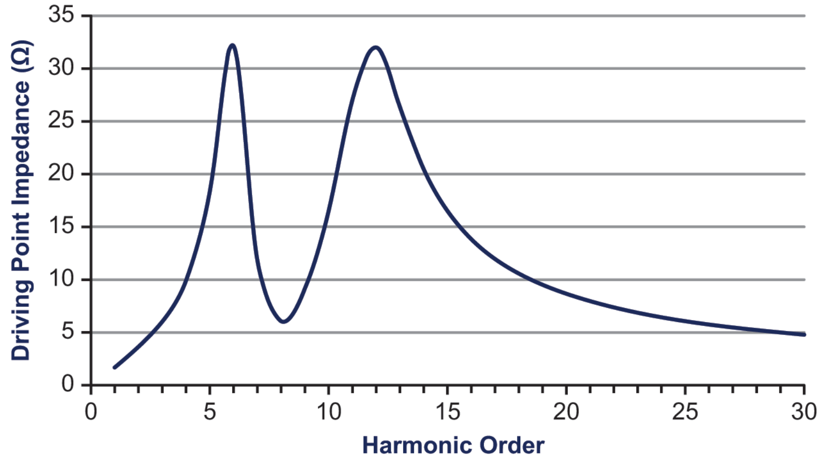


Figure 24—Driving point Impedance at the 33 kV bus

Table 11—Harmonic content of bus voltages including the effects of ASD at the 6.6 kV bus

Harmonic order	Frequency (Hz)	Voltage content in kV		
		at 220 kV bus	at 33 kV bus	at 6.6 kV bus
1	60	220	34.06	7.03
11	660	0.654	0.643	0.105
13	780	0.297	0.294	0.113
23	1380	0.117	0.122	0.023
25	1500	0.094	0.099	0.019
35	2100	0.001	0.001	0.009
37	2220	0.001	0.001	0.007
47	2820	0.016	0.02	0.004
49	2940	0.014	0.018	0.004
	THD (%)	0.333	2.13	2.24

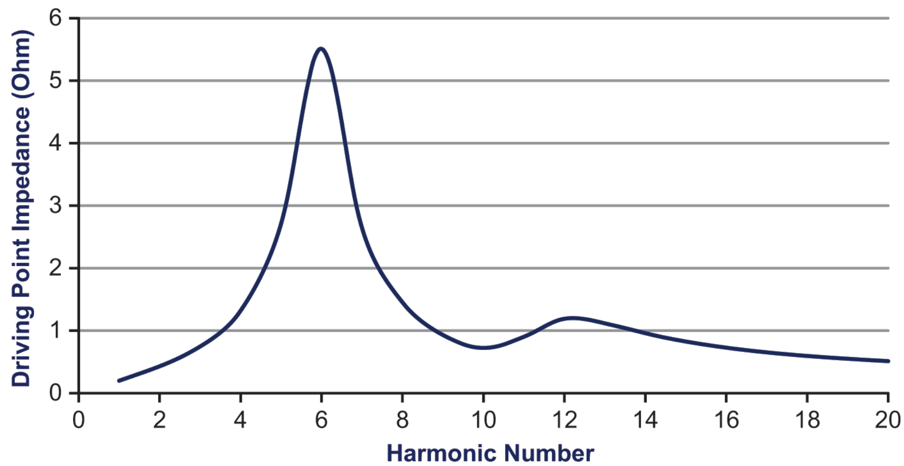


Figure 25—Driving point impedance at the 6.6 kV bus

16.3 Example 2: A 13-bus balanced industrial distribution system

Case Study 3 is taken from "Test systems for harmonic modeling and simulation" by IEEE Power Engineering Society Transmission and Distribution Committee Task Force on Harmonics Modeling and Simulation. Some system data are slightly modified. The system consists of 13 buses and is representative of a medium-sized industrial plant, shown in Figure 26.

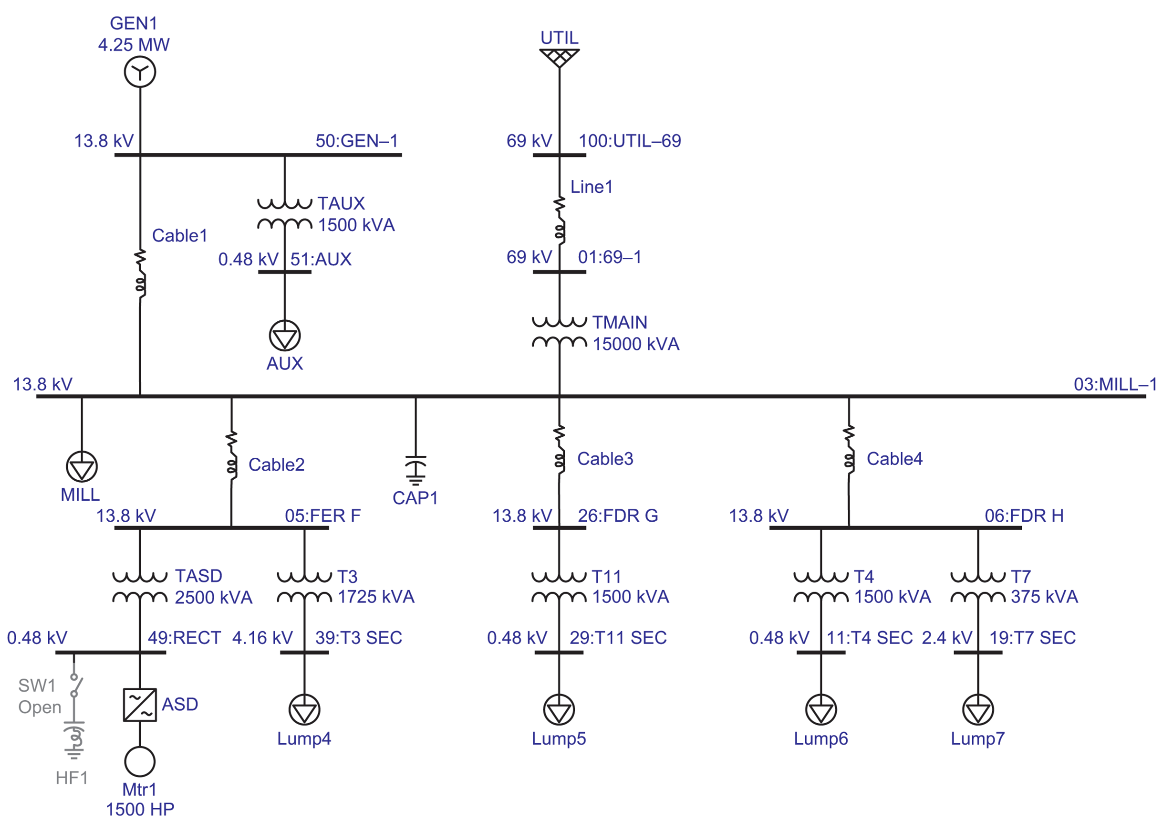


Figure 26—One-line diagram of Example 2 system

The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. A 1500 HP motor driven by an adjustable speed drive (ASD) generates harmonic currents and injects them into the system. Evaluation of harmonic voltage and current distortion inside the plant and at the Point of Common Coupling (PCC) bus need to be simulated and evaluated to determine if there are any code violations, and therefore remedy actions need to be taken.

System data including utility, generator, bus, transformer, cable, and load are found from the reference.

The harmonic current spectrum from a 6-pulse ASD at 480 V are measured and listed in the Table 12.

Table 12—Harmonic source data for ASD

Harmonic order	Percent	Relative angle
1	100.00	0.00
5	18.24	−55.68
7	11.90	−84.11
11	5.73	−143.56
13	4.01	−175.58
17	1.93	111.39
19	1.39	68.30
23	0.94	−24.61
25	0.86	−67.64
29	0.71	−145.46
31	0.62	176.83
35	0.44	97.40
37	0.38	54.36

Harmonic power flow study is performed on the system with the given harmonic source spectrum. Bus fundamental and harmonic voltages computed are summarized in Table 13. Total and individual harmonic voltage distortions for each bus need to be carefully checked and compared with harmonic limits for different types of buses listed in IEEE Std 519. If any violations are found, remedial measures need to be taken to reduce harmonic distortion below the limits.

The highest voltage harmonic distortion appears at a 480 V bus 49: RECT. This bus is a dedicated harmonic source bus from a VSD. Per IEEE Std 519, because it is within 10% it is acceptable.

Table 13—Plant harmonic voltage distortion summary

Bus	V_1	V_5	V_7	THD_V (%)
100:UTIL-69	39645.70	40.37	104.23	0.28
01:69–1	39538.00	52.36	135.14	0.37
03:MILL-1	7712.77	53.51	138.13	1.93
50:GEN1	7726.55	51.72	133.51	1.87
51;AUX	262.74	1.72	4.40	1.81
05:FDR F	7709.24	54.07	138.35	1.94
49:RECT	269.89	12.79	12.83	8.02
39:T3 SEC	2240.05	14.83	37.21	1.80
26:FDR G	7709.07	53.48	138.04	1.93
06:FDR H	7703.35	53.43	137.91	1.93

Table continues

Table 13—Plant harmonic voltage distortion summary *(continued)*

Bus	V_1	V_5	V_7	THD_V (%)
11:T4 SEC	260.40	1.78	4.59	1.90
19:T7 SEC	1302.74	8.58	21.78	1.81
29:T11 SEC	256.29	1.71	4.36	1.84

16.4 Example 3: A composite industrial power system

Sample system 3 is a sample industry complex. The system contains nonlinear load (arc furnace), electronic controlled devices (ASD, UPS), and power factor–correcting capacitor banks. It is required to perform a complete harmonic power flow study to evaluate voltage and current harmonic distortions, and determine if any harmonic mitigation needs to be considered in the system design. Also due to existence of capacitor bank, parallel resonant frequencies are to be identified by harmonic frequency scan study. Figure 27 depicts the system one-line diagram. Note that no harmonic filters are connected to the system. Displayed values shown in the diagram are total voltage and current distortions from harmonic sources in the system.

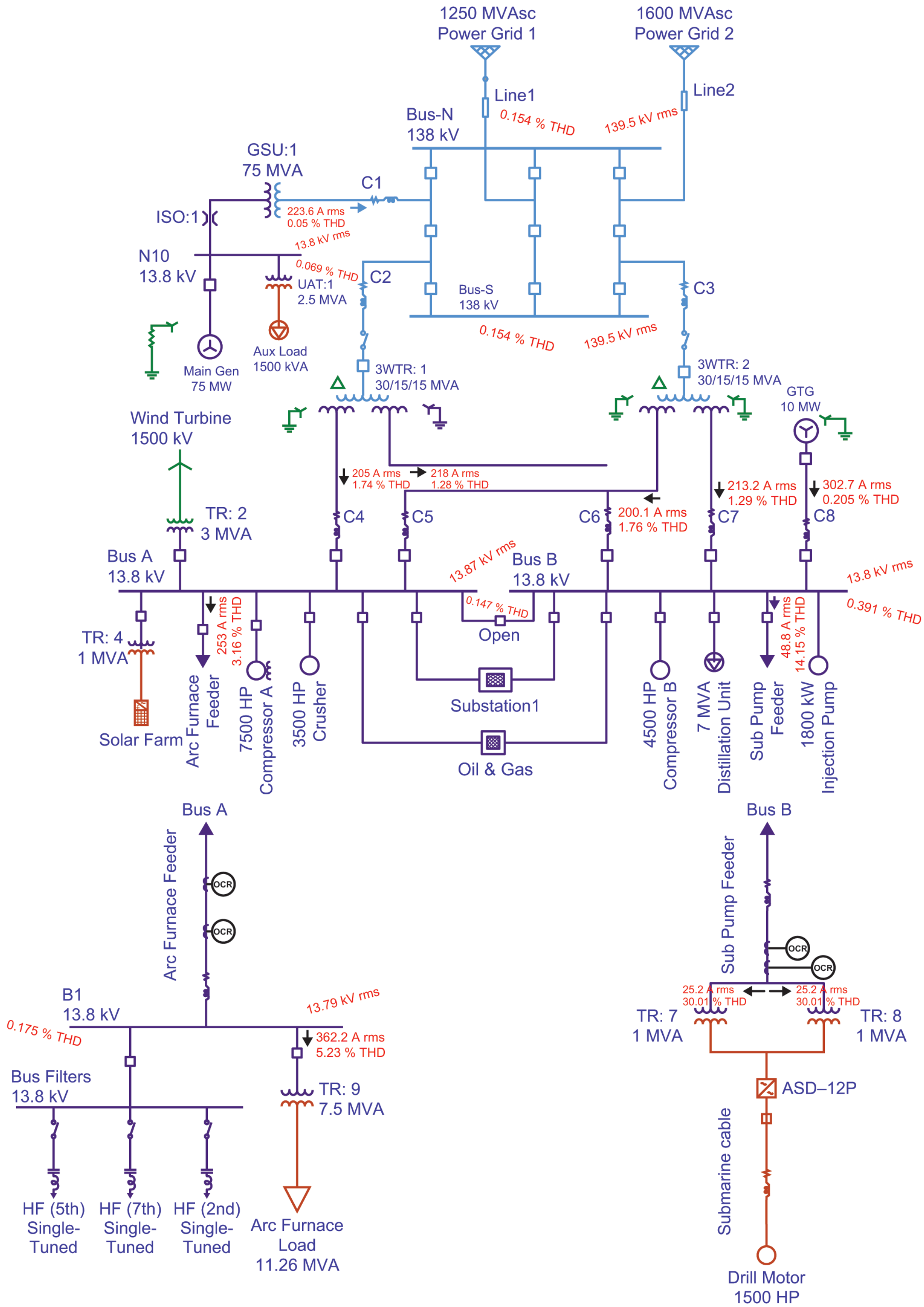


Figure 27—One-line diagram of illustration Example 3

An 11.26 MVA arc furnace load is connected to the system on 13.8 kV arc furnace bus through a dedicated transformer. A typical arc furnace harmonic voltage spectrum is assumed with data given in the following chart in Figure 28.

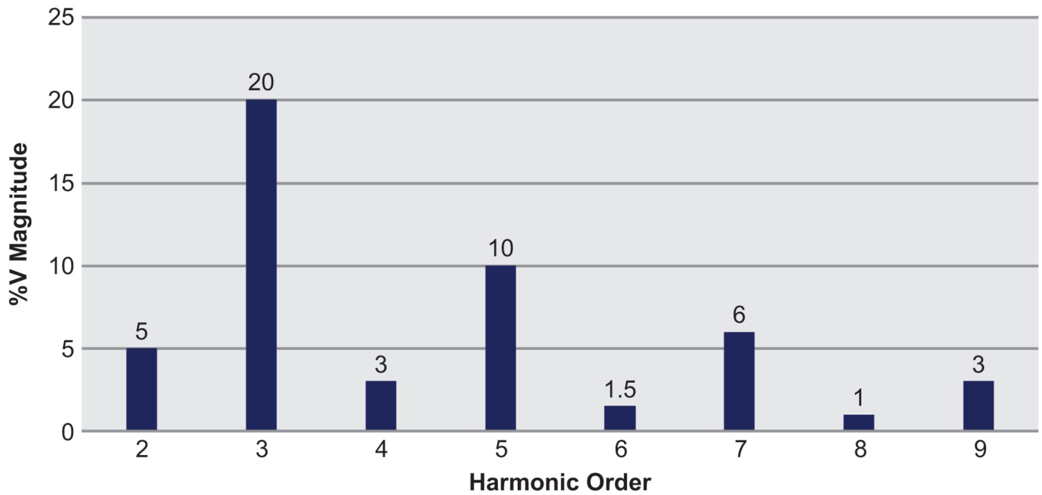


Figure 28—Arc furnace voltage harmonic spectrum (typical)

Another harmonic source is from a 1500 HP VSD connected to 13.8 kV Bus B. ASD is assumed a typical IEEE 6-pulse with current harmonic characteristics, as shown in Figure 29. Two step-down transformers TR-7 and TR-8 in parallel with special winding configurations are converting the ASD to an equivalent 12-pulse drive.

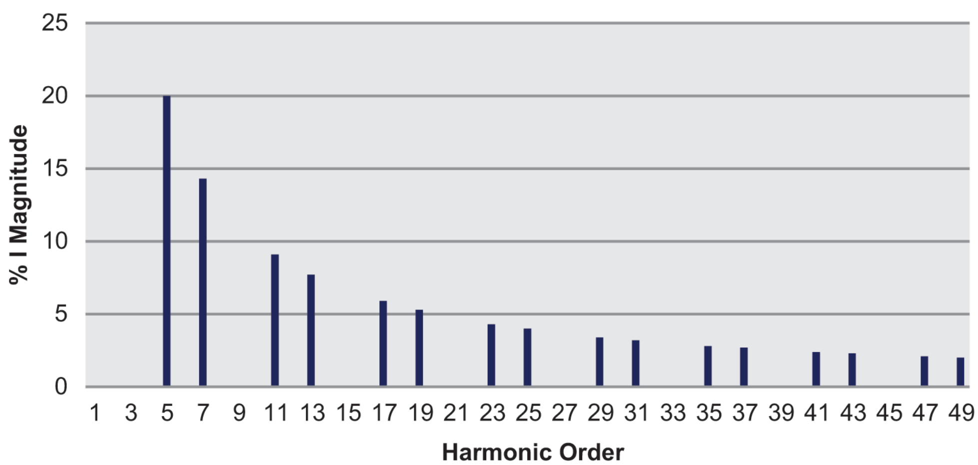


Figure 29—ASD current harmonic spectrum (IEEE typical 6-pulse)

Harmonic power flow study is conducted first. Results in Figure 30 show harmonic currents at the 13.8 kV arc furnace feeder. Note that triplen (zero sequence) harmonics are blocked by the delta connection at the primary side of transformer TR-9. The total harmonic current distortion at this cable is 5.2%.

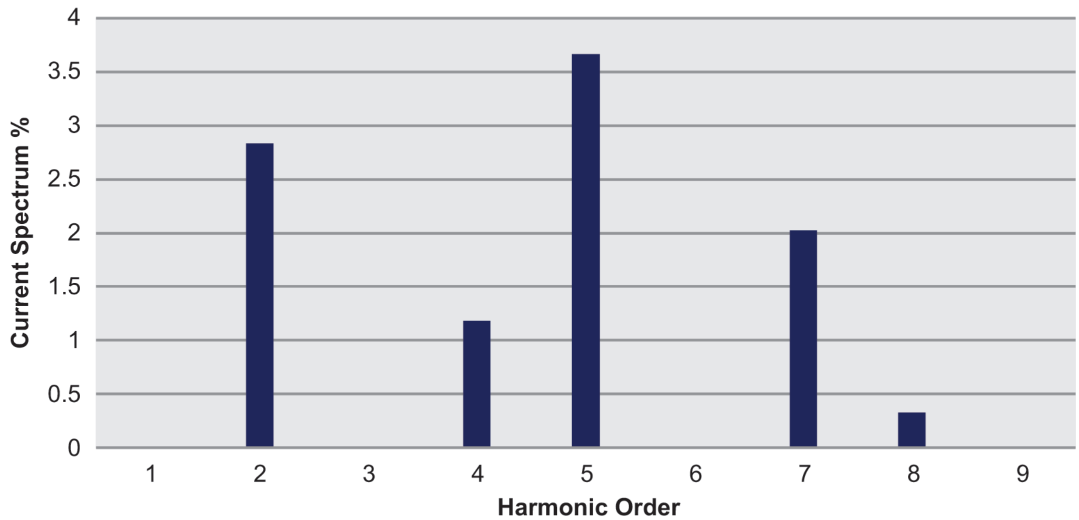


Figure 30—Arc furnace feeder current harmonic distortions (without filters)

Current distortion at the arc furnace feeder can be reduced by using *RLC* filter tuned to the frequency of interest. From Figure 30, it appears that 2nd, 5th, and 7th harmonics should be filtered out.

By designing and installing three single-tuned harmonic filters tuned to 2nd, 5th, and 7th harmonics at arc furnace bus and redoing a harmonic power flow study again, results in Figure 31 indicate reduced harmonic current injection into the system by the arc furnace harmonic source through arc furnace feeder. The total current harmonic distortion drops from 5.2% to 1.5% as shown in Figure 32. Load flow study verifies the power factor for the arc furnace feeder flow, also improved from an original 31.11% to −18.09% as a benefit of the capacitance from the installed filters.

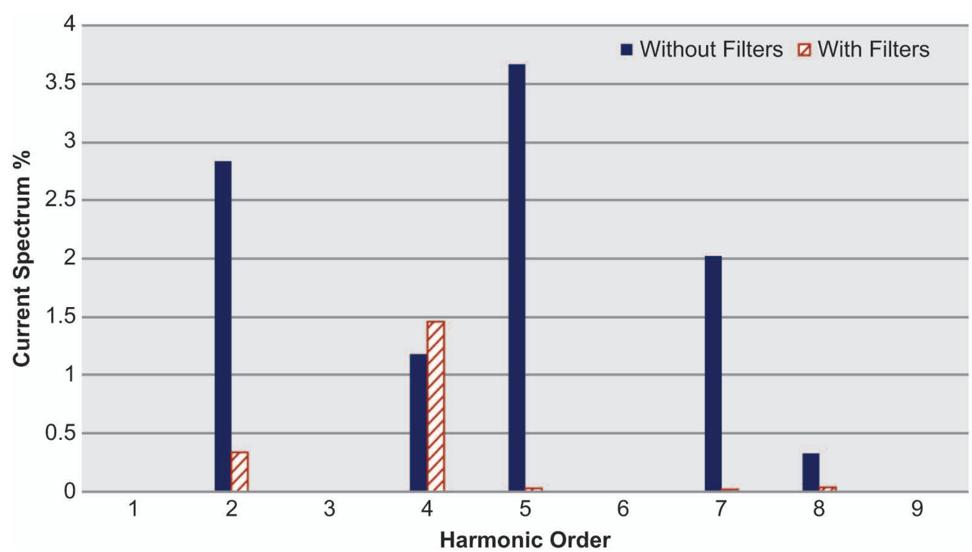


Figure 31—Arc furnace feeder current harmonic distortions (comparison at 13.8 kV)

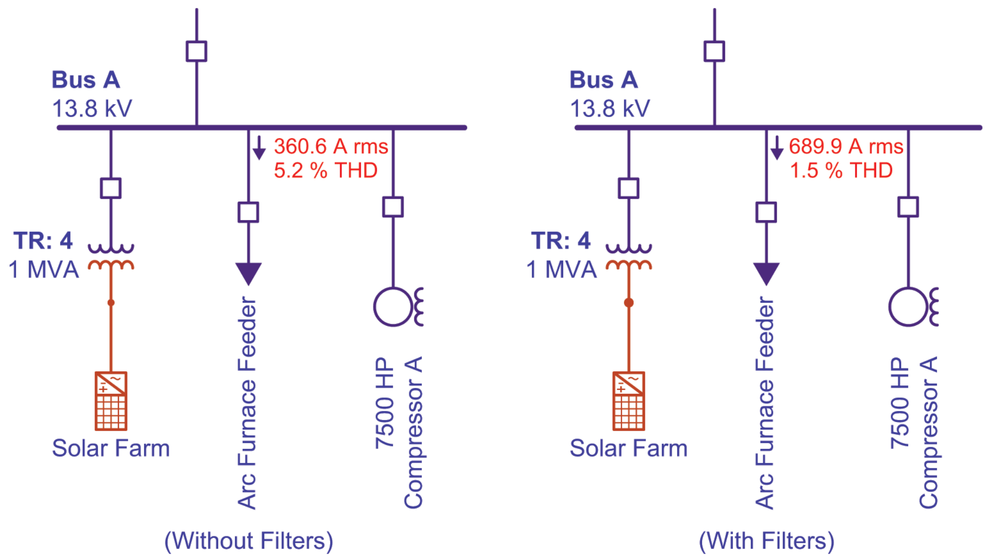


Figure 32—Reduced harmonic current distortions

Using harmonic power flow study, harmonic cancellation through parallel transformers with phase shifting can also be validated. Figure 33 shows parallel transformers TR:7 and TR:8 that have 30 degrees phase shifting from one to another. Figure 34 shows harmonic currents on load side (a) and line side (b). It clearly shows harmonic cancellation due to transformers connected in parallel.

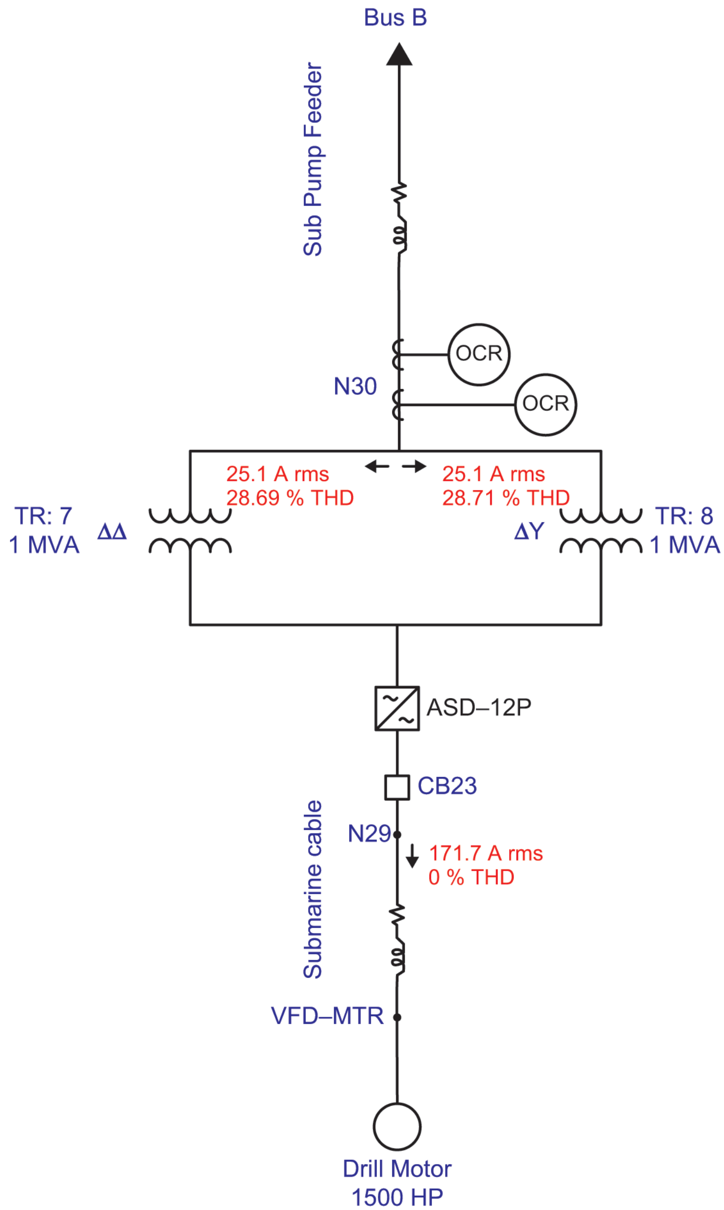
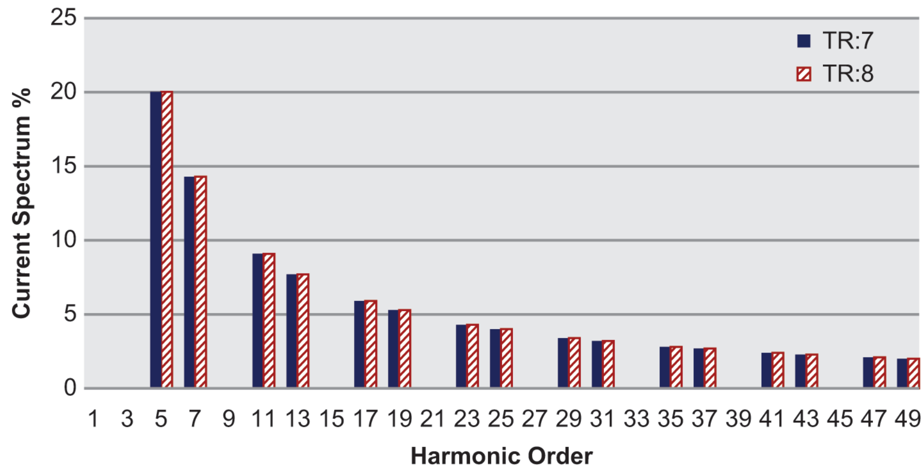
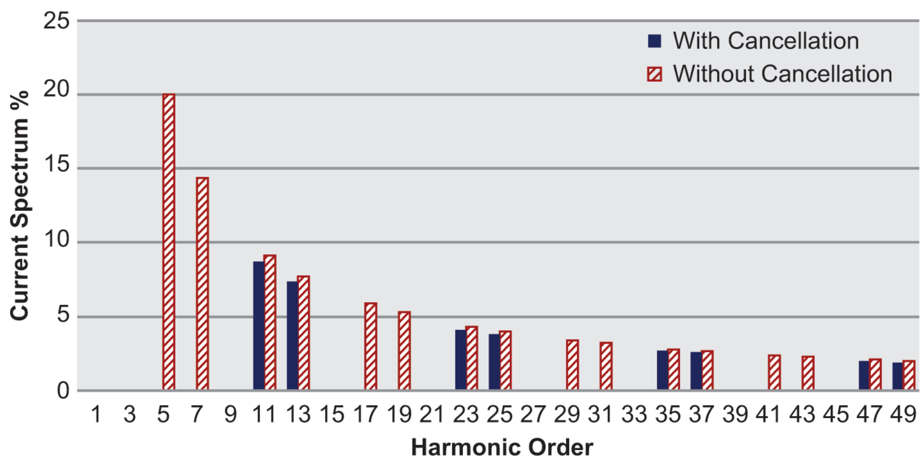


Figure 33—Harmonic currents from ASD and cancellation by phase-shift transformers



(a) Current harmonic spectrum for transformer TR:7 and TR:8



(b) Current harmonic cancellation from parallel phase-shifting transformers

Figure 34—Current harmonic cancellation from parallel phase-shifting transformers

Finally, a harmonic frequency scan is performed to detect any parallel resonances and assess potential issues. Figure 35 shows a frequency scan result at Bus 1A where a capacitor bank is installed. The result shows one single parallel reassurance frequency around 11th harmonic. If the bus has harmonic current injection near this frequency, potential harmonic overvoltage may occur and remedy action needs to be taken to remove or shift the resonance frequency.

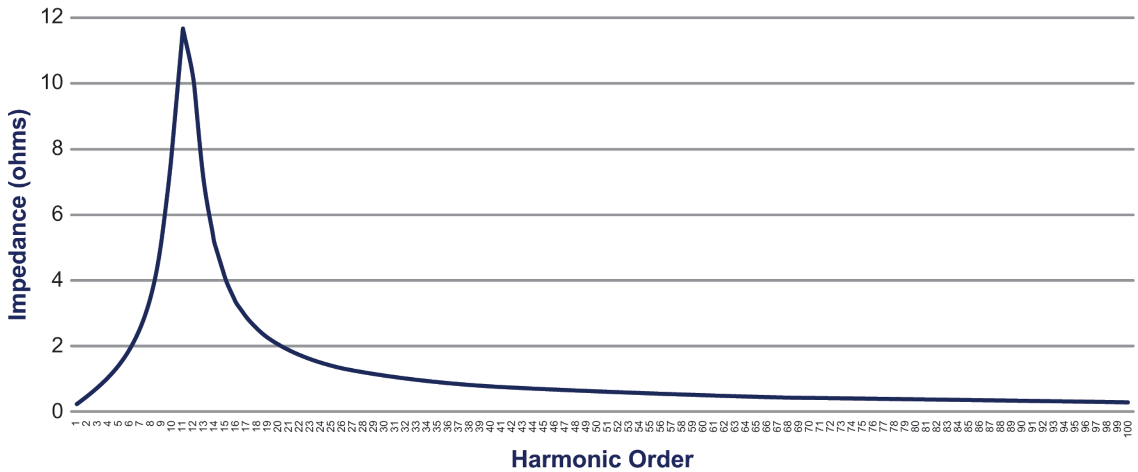


Figure 35—Bus 1A driving point impedance frequency characteristics

Annex A

(informative)

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